A Thesis Report on

INVESTIGATION OF CVT-BASED HYBRID MECHANISM FOR TORQUE VARIATIONS IN A KNEE EXOSKELETON

Submitted in partial fulfilment of requirement for the award of degree of

MASTER OF ENGINEERING
IN
CAD/CAM ENGINEERING

Submitted by

BALTEJ SINGH RUPAL

Roll No. 801481005

Under the Guidance of

Dr. ASHISH SINGLA

Assistant Professor,

Mechanical Engineering Department,

Thapar University, Patiala

MECHANICAL ENGINEERING DEPARTMENT

Thapar University, Patiala

July, 2016

DECLARATION

I hereby declare that the thesis report entitled, "**Investigation of CVT-based Hybrid Mechanism for Torque Variations in a Knee Exoskeleton**" is an authentic record of work carried out as requirement for the award of **Masters of Engineering in CAD/ CAM Engineering** during 4th semester (Jan 2016 – July 2016) at Thapar University, Patiala under the supervision of **Dr. Ashish Singla** (Assistant Professor, Mechanical Engineering Department).

Baltej Singh

Date: 28 June 2016

BALTEJ SINGH RUPAL

Roll No. 801481005

This is to certify that above declaration made by the student concerned is correct to the best of my knowledge and belief.

Dr. Ashish Singla
Assistant Professor
Mechanical Engineering Department
Thapar University, Patiala

Countersigned by:

Dr. S. K. Mohapatra
Senior Professor and Head
Mechanical Engineering Department,
Thapar University, Patiala

Dr. S. S. Bhatia
Dean of Academic Affairs,
Thapar University, Patiala

ACKNOWLEDGEMENT

I would like to express my sincere and devoted gratitude to **Dr. Ashish Singla**, for his continuous encouragement, support and guidance throughout this work, without which this wouldn't have been completed. He has always guided me in every step of this work and has always taken pains to solve any problems, difficult situations whatsoever. I also thank him for providing me with this wonderful opportunity to work in an international collaboration with Prof. Gurvinder Singh Virk.

I am extremely thankful to **Prof. Gurvinder Singh Virk (University of Gävle, Sweden)** for his constant guidance in this project work via e-meets and emails. It's been a privilege to have such an expert by our side. I am pretty sure that his inputs and brilliant ideas will take this project to new heights in near future.

I am grateful to my team members Gurminder Singh and Saurav Dhand who helped me through the thick and thin in this project work. I would like to thank all the faculty members of the Mechanical Engineering Department for their help and encouragement. I also thank my parents, younger brother and my dear friend Alice Goyal for their unceasing encouragement and support. Motivation from all my friends has also played a great role in progress of my thesis work. Last but not the least; I also place on record my sense of gratitude to one and all who, directly or indirectly, have lent their helping hand in this venture.

BALTEJ SINGH RUPAL

Roll No.: 801481005

ABSTRACT

One of the major problems faced by elderly people is independent mobility. Till now, widely accepted conventional mobility solutions are crutches, wheelchairs, and walkers etc., which hardly give any independence and have other disadvantages also. To provide a better mobility solution, interest in wearable exoskeletons is increasing. It is important, to focus on the growing needs of the elderly people as assistive exoskeletons have the potential to play a major role in helping elderly persons to maintain independence and good quality of life. This thesis provides a crisp review of state-of-the-art in exoskeletons by providing a classification methodology, comparing their constructional features and also critically analysing the pros and cons of systems which have been realized. Regulatory issues, important for realizing new markets for the technologies, are also explored in this work. Main focus of the thesis is to explore new technologies to make the exoskeleton more cost effective so that it can be accessed by the masses. Torque variation methods of the exoskeletons are surveyed and a new cost effective solution is investigated by using Continuous Variable Transmission (CVT) and conventional mechanisms. The feasibility of a step cone type CVT to provide torque variation for sit-to-stand motion at knee joint is investigated by using optimization methods in MATLAB environment. The torque range data for the optimization purpose is taken from the experimental results from our Swedish group. Optimized CVT is then coupled with a scotch yoke mechanism for motion reversal and four-bar chain for poly-centricity at the knee joint by developing a mathematical model. Then geometric modeling of the complete assembly is made and simulation is done in MATLAB/Simulink. For validation, the results are compared with walking gait cycle of the normal healthy human being. Future work will focus on finding more alternate cost effective methods and the experimental validation of the results by prototyping and testing on human subject.

CONTENTS

List of Figures

List of Tables

List of Publications

1. Ashish Singla, Baltej Singh Rupal, Gurvinder Singh Virk, "**Optimization of cone type continuous variable transmission for lower limb exoskeletons**", International Conference on Engineering and Material Sciences (ICEMS-2016), JNU-Jaipur, India, 2016.
   [Accepted in **'Perspectives in Science' – Elsevier Journal**]

2. Baltej Singh Rupal, Ashish Singla, Gurvinder Singh Virk, "**Lower Limb Exoskeletons: A Brief Review**", 22nd National Conference on Mechanical Engineering and Technology (COMET-2016), IIT(BHU), Varanasi, India, 2016
   [Won 2nd prize in Biomechanics Category and published in **International Journal for Scientific Research and Development- IJSRD**]

3. Gurvinder Singh Virk, Ashish Singla, Baltej Singh Rupal, "**Lower-Limb Exoskeletons: Current Developments, Regulatory Issues, Challenges and Future Trends**", Robotics and Autonomous Systems (Elsevier), 2016
   [**Submitted and Under Review**]

4. Baltej Singh Rupal, Gaurav Garg, Tarun Bharadwaj, Ashish Singla, Gurvinder Singh Virk "**Actuation Mechanism for Knee Joint of a Powered Lower-Limb Exoskeleton for Torque Variation and Motion Reversal**", Journal of Rehabilitation and Assistive Technologies Engineering (SAGE), 2016.
   [**Submitted and Under Review**]

Chapter 1

Introduction

Elderly people tend to lose their independence and have to depend on others for their basic necessities and for carrying out essential daily chores. They require support for local mobility from one place to another, e.g. crutches, wheelchair, walkers etc. All these conventional methods, as shown in Fig. 1.1 fail to provide independence to the user and they have to rely on someone else. Electrically powered walkers or rehabilitation devices are also available but these devices are not very effective. They could not solve basic problems faced during the use of these devices even if the people do not use the devices but employ an assistant or a family member for helping them.

Fig. 1.1 Conventional personal mobility solutions [7]

The major problems faced by elderly people are:

- inability to sit, stand, perform transfers and to walk
- need for personal assistance at home
- risk losing independence
- reduced quality of life
- financial problems to employ carers

To eradicate this problem of dependency and to give elderly people an autonomous mobility solution, robotics came into rescue. A wearable robotic device is the new technology which eradicates these problems and gives a sense of satisfaction to the elderly people.

1.1 Origin and Need of Lower-Limb Exoskeletons

The term ‘wearable robotics’ came into general existence in the 1960s when USA and Yugoslavia starting the research in load carrying augmentation and rehabilitation systems respectively [1] and interest continues to grow with new innovations reported regularly. Essentially exoskeletons are wearable devices, which can help human wearers perform a variety of normal daily living motion tasks such as walking, carrying loads, ascending or descending stairs, sit-to-stand (and vice versa) transfers, moving around generally, etc. Fig 1.2 shows the basic components of an exoskeleton device.

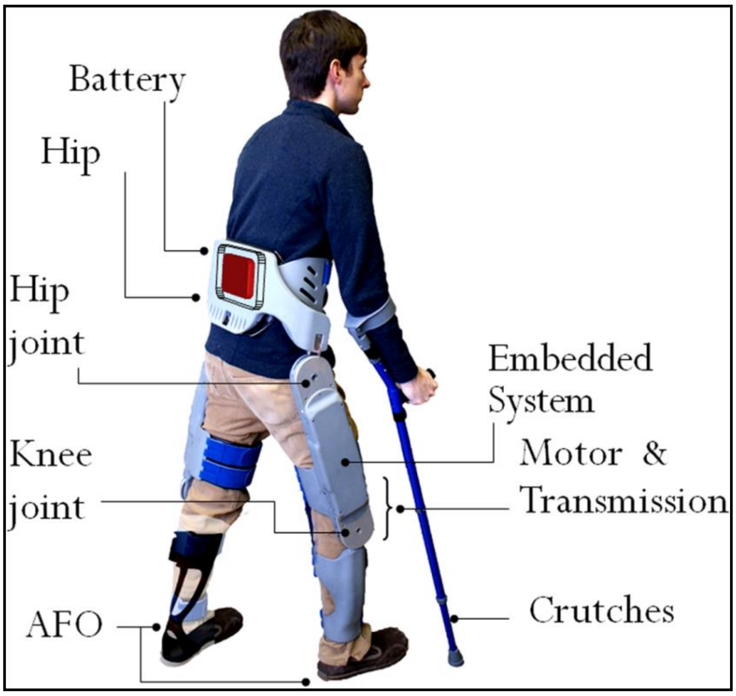


Fig. 1.2 Exoskeleton worn by a human bring showing its all major parts [73]

Till date, the thrust of exoskeleton research has focused on medical applications such as spinal cord injured persons and rehabilitation of major trauma patients as well as how soldiers can carry heavy loads and march at high speeds in rough terrain. Recently, due to ageing societal concerning new scenarios for providing assistance to elderly people for daily living activities has started to receive attention. The reason for this is the growing urgency for assistive systems to help elderly people remain independent. As humans age, they start to have physical and cognitive issues and when these become severe, are no longer able to do basic activities and need care support to help us. An important issue in being independent is our capability of personal mobility. If they can continue to move around, they can stay active and thereby continue to live in our own home with good quality of life for as long as possible. Physical assistive exoskeletons can help in such situations and, in addition, reduce the burden on health care resources. UN population statistics [2] presented in Fig. 1.3 suggests that the ageing population will rise globally and the need for healthcare support will grow. To reduce the burden on government care services, many programs have been set up to promote research and development of assistive care technologies such as exoskeletons to meet the perceived needs in the near future.

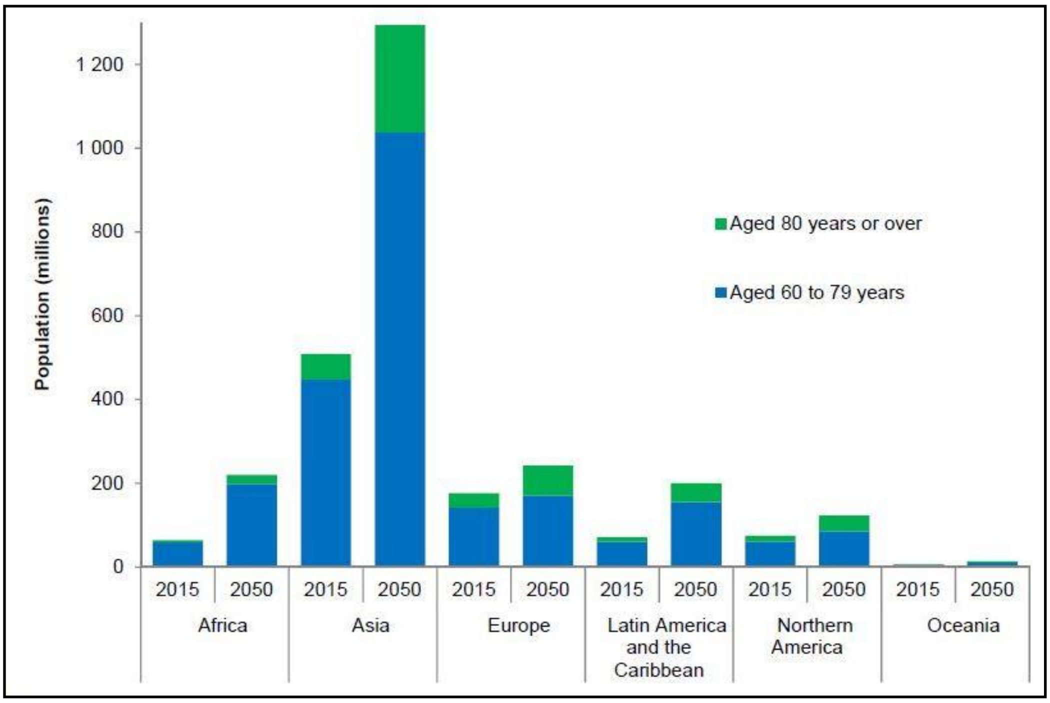


Fig. 1.3: Population of elderly, estimated for 2015 and projected for 2050 [2]

The focus of exoskeleton research over the last 20 years has been on medical applications to provide mobility to spinal cord injured patients or rehabilitation of major trauma patients to train them to make basic movements again after suffering a stroke. A recent review paper on lower-limb exoskeleton thoroughly discusses the issues related to performance, user interfaces and control strategies [3]. Less attention has been given to assistive exoskeletons (which are not medical devices) to help healthy elderly people for normal daily living. Survey papers from the last 10 years

[4-8] suggest that this area is hardly touched, and so it is given more emphasis in the current research. The key differences in designing medical and non-medical (assistive) exoskeletons are highlighted so that researchers can give the non-medical application scenarios more attention that is needed to ensure the needed assistive scenarios can be more thoroughly investigated and appropriate solutions realized. A survey of the existing exoskeletons developed is carried out in next chapter using this application based approach so that the particular requirements of the different sectors can be presented and identify the future trends needed.

1.2 Key issues

Exoskeletons are broadly classified into two major categories: *medical* and *non-medical* exoskeletons. The key issues that need to be considered when developing assistive technologies for healthy elderly persons compared to medical exoskeletons scenarios are the following:

- In medical cases the motion trajectories for individual joints do not exist as the patient cannot make the required movements, whereas normal healthy elderly persons normally still have significant physical functionality which needs to be "topped up" rather than having to have it "fully replaced" as in SCI (Spinal Cord Injured) persons. This means technical issues such as user interface, control strategy, mechanical interface etc. need to be designed specifically to cater for the individualistic needs of the patient. Often medical exoskeletons require specialist medical professionals to deploy and use them so that maximum benefit can be given to the patient and harm is prevented.
- For non-medical applications, methods for measuring motion "user intention" is most important so that the actuated mechanisms can be operated to support the user intentions in as natural a manner as possible. For maximum effectiveness and acceptability, simple and natural interfaces are needed so that lay users can don, operate and doff the exoskeletons easily and quickly. The interfaces need to be generic enough to have mass appeal but be sufficiently adaptive to meet wide range of variations found in the movement patterns of individuals

- The international regulatory requirements (published by ISO/IEC) for medical and non-medical products are different and must be complied with for successful commercialization. It is important to be aware of what is being developed, i.e. is the wearable robot a medical device for patients or a personal care exoskeleton for healthy persons so that the correct risk assessment and management can be carried out. This means identification of relevant medical device or machine safety standards.
- The physical functionality of elderly persons degrades with age and hence a flexible and adaptable assistive technology needs to be developed so that the level of assistance can automatically adapt to meet the growing need in an individual level rather than having to routinely change the exoskeleton. An important to note here is that, although ageing is normal and does not need to be a medical issue, ageing normally involves some "medical condition" to arise and this needs to be considered in the design of the exoskeleton. If the medical condition is relevant to the motion aspects then it is likely that the exoskeleton should be classified as a medical device; on the other hand if the medical condition is not related to the mobility being supported, the assistive exoskeleton can be a non-medical system and consumer regulations can apply making the product main stream and available in retail stores without involvement of medical practitioners.
- Researchers are starting to give attention to these requirements for wearable exoskeletons so that effective solutions can be realized and replace the limited number of systems currently available for supporting personal mobility of individuals, namely, wheelchairs, crutches, sticks, mobility scooters, etc. Simple aids like sticks and crutches are acceptable for low-level or short-term help but can be ineffective when high-level support is needed. Wheelchairs and mobility scooters are fine for general mobility in large open plan areas but require major life changes have to be made to adopt them in homes. Wheelchairs often have to be adopted as there are no other viable alternatives but people are forced to move to single storey apartments, install chair lifts and ramps, change fittings because they are too high or too low, etc. Such changes can impose significant financial costs on an individual even though the actual cost of the wheelchair or a mobility scoter could be quite low and acceptable; the overall costs for effective adoption can be huge. Replacing these traditional wheel-based mobility solutions by body-fitting

exoskeletons will mean minimal changes need to be made to homes and life-styles for staying active and independent living in one's home for as long as possible.

Having presented the overall issues for wearable exoskeletons, detailed discussion is started by presenting a review of existing exoskeletons based on application so that the different requirements can be highlighted and how these should be explored in the future to meet the global trends. Then for streamlining the research, it is focussed on torque variation and motion reversal methods and did a comprehensive literature survey into the torque variation methods and motion reversal techniques. In this report traditional mechanisms are considered and linkages for torque variation and checked its feasibility in lower-limb exoskeletons.

1.3 Scope of the Thesis

The elderly population in our society is increasing and hence societal issues related to ageing problems are also increasing. One of the key issues facing elderly persons relates to personal mobility which is essential for independence and good quality of life. With advances in technology, conventional methods like walkers, crutches and wheelchairs for providing mobility are being overtaken by wearable robots, commonly known as exoskeletons. This technology represents the future of mobility solutions for the elderly. Many research institutes and commercial undertakings are putting efforts to come up with a general purpose exoskeleton able to meet the needs but still an effective and affordable solution is required to be developed for the masses.

The future of assistive exoskeletons is bright and such devices are widely predicted to be in high demand to meet the needs of the global ageing society. Also as many commercial undertakings are emerging to develop commercially viable solutions it is foreseen that elderly people will have access to affordable exoskeleton devices for ensuring that they are able to move around independently and maintain good quality of life in their own homes for as long as possible. Avoiding high cost sophisticated components like harmonic drives, microcontrollers, and high end DC motors and looking into ergonomic mechanical innovations can help improve the quality of the exoskeletons delivered to the markets. Therefore, if proper emphasis is laid on these issues, the exoskeleton market can be developed to reach the masses to provide the needed assistive devices. Moreover, with reduction in cost the demand of exoskeletons will increase not only in developed countries but in developing countries and regions such as India, China and Africa.

1.4 Organization of the Thesis

The organization of the thesis is given below:

In **Chapter 2**, the state of the art of the exoskeleton devices is presented with keeping focus on the technology advancement of the exoskeletons which specifically target elderly people and patients. The whole domain of the exoskeletons is categorized and explained in sub-categories in detail. Finally a comparison table is made which gives an holistic idea about the current state of the technology and the directions for the research work.

In **Chapter 3**, literature gaps are identified and further developed into a proper problem formulation. Two major areas are found out, first is the torque variation techniques and the other is human powered products for exoskeletons. Further, the standardization and regulation issues related to the exoskeleton devices are discussed in detail as it affects the design conditions of the device.

In **Chapter 4**, the concept of continuous variable transmission (CVT) is introduced for exoskeletons and its literature is studied to find out the most suitable CVT for use in exoskeletons for purpose of torque variation according to user need. Various types of CVTs are discussed in detail and a comparison table made which gives relevant idea about the advantage of using Cone CVT in exoskeletons.

In **Chapter 5**, the optimization of step cone CVT is done by mathematical formulation of the objective function and stating the constraints of the function. The data of human walking from Swedish group is used to find out the optimal values of the dimensions of the CVT which will be further used in conjunction with mechanisms to provide required torque at the knee joint of the exoskeletons.

In **Chapter 6**, various mechanisms are explored and their usage in the exoskeletons is discussed for the purpose of torque variation and motion reversal. Scotch yoke mechanism and four bar mechanism are used for this purpose. Complete system is developed analytically and geometrically for simulation purpose. Finally the results obtained from both the approaches are validated with normal human walking cycle.

In **Chapter 7**, conclusions of the thesis work with the results are discussed and the future directions, in which the work can be extended, are given briefly.

Chapter 2

Literature Review

2.1 State of the Art

For a comprehensive survey, the exoskeletons are classified into two broad categories, namely *medical* and *non-medical*. These are further subdivided according to application and need as shown in Fig. 2.1. The main focus here is to highlight the mobility issue of the wearer, and only full-body or lower-body exoskeletons are considered. Upper-body exoskeletons do not contribute significantly to mobility and hence are omitted. Going further into the literature review, it was found that the exoskeletons can be classified into different categories. However, there are few exceptions due to multi-fold applications of particular exoskeletons, which create a dilemma about the explicit category, in which that exoskeleton should be placed.

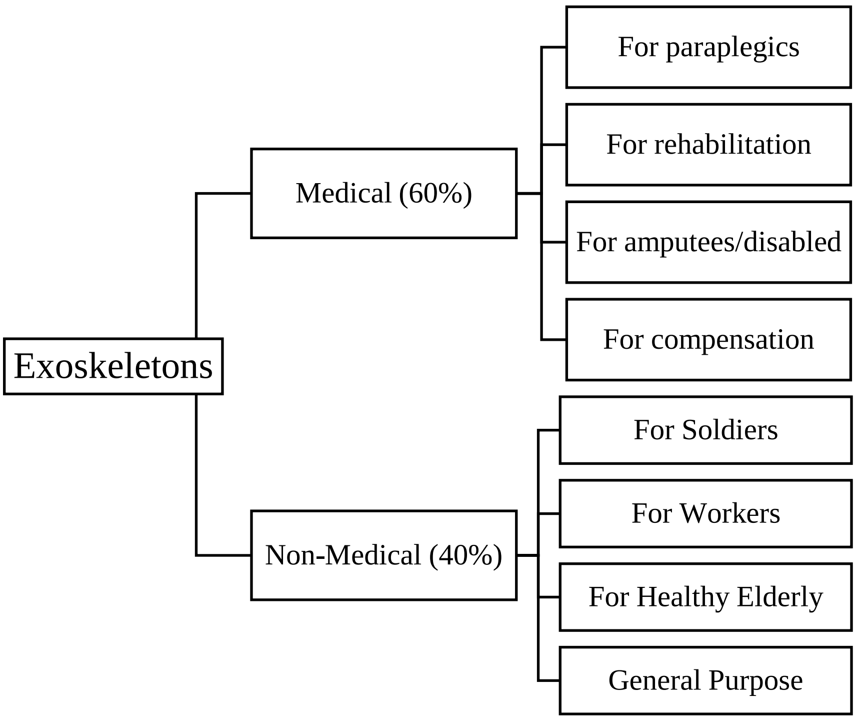


Fig. 2.1: Classification of exoskeletons

From the all exoskeletons studied, 60% belong to medical category and 40% to non-medical, as shown in Fig. 2.1. Further, a comparison table is developed in the paper, through which the various exoskeletons are compared on the basis of their purpose, DOF, actuator type, weight, battery-life etc. In this table, most of the data is taken from the published literature and patents. In some cases, the data is available on internet, videos or commercial websites, so the facts and figures should be taken as suggestive. In the next subsection, each subcategory of Fig. 2 is discussed.

2.2 Medical Exoskeletons

This category includes exoskeletons which are used to provide mobility to physically disabled, injured or weak persons, who are unable to walk due to certain medical reasons such as spinal cord injury, major trauma like stoke, neuro-logical issues, etc. In this category, the exoskeletons are designed for a specific joint/limb, which has limited mobility, like upper-limb exoskeletons or lower-limb exoskeletons. In this survey, only lower limb exoskeleton systems are considered to discuss the technology trends in how the mobility issues are catered for. The domain of the upper-limb exoskeletons is discussed in a comprehensive manner by Mann *et al.* [9]. In lower-limb exoskeletons, important medical application sub-categories are explained next.

2.2.1 For Paraplegics

Exoskeletons in this category are used to assist patients suffering from paraplegia. Paraplegia is a type of paralysis as explained in Fig. 2.2, which is the inability in the motor or sensory functions of lower limbs preventing basic motions such as standing and walking. In order to take care of this reduced lower-body functionality, a number of conventional methods were in practice like the use of braces and crutches, wheelchairs and orthotic devices. Braces and crutches fail to provide 100% autonomy to the person. The mode of locomotion through conventional wheelchairs has its own pros and cons as already stated. Wheelchairs provide effective movement on flat surfaces but cannot be used on all terrains and result in excessive sitting in one posture.

Moreover, wheelchairs do not permit eye level interactions, which is a major social issue. Other locomotion options use different orthotic systems like FES (Functional Electrical Stimulation), KAFOs (Knee-ankle-foot orthoses), RGO (Reciprocal gait orthoses). It has been reported in the literature [10] that FES systems were successful for short distance ambulation only, however results in high energy consumption and muscle fatigue. Compared to conventional KAFOs, which are heavy and difficult to wear, the RGOs offer better ambulation over short distances [10]. As presented in Table 2.1, there are several devices developed for upright walking of paralyzed people.

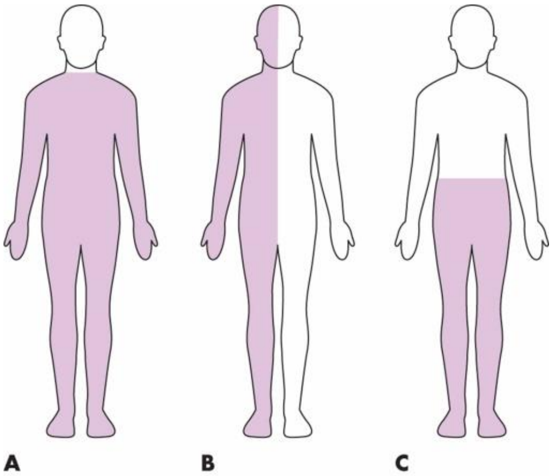


Fig. 2.2: Types of Paralysis, colour portion is paralyzed
A. Quadriplegia, B. Hemiplegia and C. Paraplegia [31]

A good example is ReWalk [11], which has been developed for patients suffering with spinal cord injury (SCI). As a user worn backpack device, ReWalk is a self-contained exoskeleton which uses rechargeable batteries to derive the hip and knee joint motors. It uses a tilt sensor to calculate the trunk angle and a wrist-watch style controller to activate different motion modes such as stand-sit or walking. Another example for SCI applications is the Indego exoskeleton developed and commercialized by Vanderbilt University [12]. It consists of three portions, namely a hip brace, 2 thigh frames and 2 shank frames which can be assembled quickly for wearing it. It has been developed to be used with a conventional set of ankle-foot orthoses and is claimed to be easy to put on, take off and to be adjusted for good fitting single handedly. It has 6 modes for sitting, standing and walking and the transitions between these motion modes. Other exoskeletons like Ekso [13], Rex [14], Atlante [15], Mindwalker [16] have also been developed for SCI and paraplegic patients. They are briefly explained in Table 2. Exoskeletons like ReWalk, Ekso, and Rex have been commercialized as high value medical products but the evidence of their real usefulness is still in doubt as there are still technical and social issues which need to be addressed for making them commercially successful and useful to society.

2.2.2 Rehabilitation Applications

Rehabilitation is needed for persons with gait disorders, which can result from a variety of medical conditions such as lesions in the central nervous system caused by spinal cord injury, cerebrovascular accidents, cerebral palsy, etc. Gait disorders force the person to depend on wheelchairs for mobility as the only viable way of performing stable movements. They become unable to carry out normal daily-life and social activities. Lower-limb exoskeletons have been presented as a possible solution [17] for these people as the medical devices can help the patient to restore their walking ability to become independent again. Medical gait training exoskeleton devices come into this category and they are usually treadmill based and are stationary in nature. Treadmill type gait-training exoskeleton devices do not fully come into the domain of wearable exoskeletons as they do not support normal daily activities but they use the same technology to retrain a patient to re-learn a lost function in normally a stationary set-up. Chen *et al.* [18] have comprehensively explained the use of gait training devices and lower-limb exoskeletons for such rehabilitation applications with/without BWS (body weight support) where 6 types of exoskeletons as shown in Fig. 2.3 have been explained.

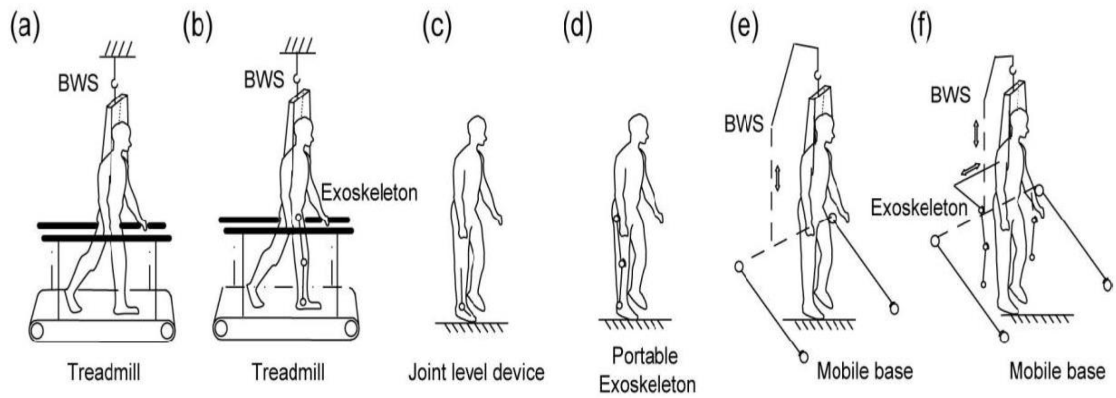


Fig. 2.3: (a) Treadmill-based BWS system, (b) Treadmill-based exoskeleton, (c) Joint level device, (d) Portable exoskeleton, (e) Mobile robotic trainer, (f) Exoskeleton with mobile platform [18]

An exoskeleton named 'Lokomat' developed by Hocoma is a treadmill based BWS device which includes audio-visual biofeedback, using a screen in front of the user; it is powered at the hip and the knees. Other rehabilitation exoskeletons like Lokomat

[19], Lokohelp [20] etc., fall into this category and are briefly discussed in Table 2. Exoskeletons that are treadmill based have essentially two points to consider for their improvement, namely comfort and satisfaction of the patient and cost to medical and healthcare organizations as they are limited to clinical use.

2.2.3 For Amputees

Amputees are persons who have one or more limbs removed due to causes such as accident, trauma, or medical illness. For restoring the mobility of amputees, various devices are used e.g. walkers, braces, orthotic devices, artificial limbs, etc. These medical devices attempt to restore the mobility of the person as best as possible but are normally limited in their functionality. For improved restoration of personal mobility in such cases, better fitting and functioning 'robotic prosthetics' need to be used which not only support the person in providing the missing limb but also how it should be actuated and controlled during various human motions. Such robotic prosthetics fall into the category of medical wearable devices and hence exoskeletons [21].

Fig. 2.4: Types of amputation- 1. Amputations in the hip and pelvis region, 2. Transfemoral amputations, 3. Amputations in the knee (knee disarticulation), 4. Transtibial amputations,
5. Amputations on the foot [24]

Research in this area is gaining pace as society is accepting the technology in preference over conventional methods wherever possible. Specific products are manufactured according to the needs of the user and type of amputation. Some examples are shown in Fig. 2.4, e.g. for a trans-femoral amputee (above knee), the device comprises a knee prosthetics, a socket, an ankle-foot prosthetics and a link between them. Ottobock [22] is a world leader in such robotic prostheses and orthoses and its ‘C-Leg’ product is popular with trans-femoral amputees; the device weighs around 1.2 kg and is made of carbon frame. It has an on-board microprocessor for mapping the actuator feedback and is claimed to be very comfortable compared to other similar products. Other notable devices include the prosthetic foot made by Ossur [23], etc.

Hydraulic actuators were also used to power knee prostheses which gave high resistive torques and it is claimed that users feel more security and stability in the various motion stance phases during walking [21]. However, with the growing introduction of electronics, such hydraulic components are being phased out and the use of the term ‘intelligent prostheses’ has been growing. The term basically means some form of “smart” control of energy generation and dissipation at the supported joint. Intelligent prostheses have changed the outlook of the prostheses industry, but some pending issues still remain; these include weight and size incompatibility and overall efficiency of the electro-myographic sensors used. The next era is expected to comprise ‘cybernetic prostheses’ which will incorporate more robotics technology to assist the amputees. Bio-inspired robotics is also the part of this trend. The control strategies, reproduction of gait patterns will utilize solutions from nature and advances made in science and engineering. In the future, it is expected that such cybernetic prostheses will be common and widely used by amputees to regain their mobility and be able to move around like healthy persons without getting noticed.

2.2.4 For Compensation of Lost Functions

This category includes multi-purpose power assist systems where the intention is to replace or restore a lost function and is again related to the medical sector. Examples are wide and varied and can include the ‘nurse power assist’ [25] designed for medical staff to help carry patients in hospitals and care institutions to reduce injury or fatigue. In this device, pneumatic rotary actuators were used and installed on the back of the nurse (wearer) to take the weight of the patient. Another device, namely the Pheonix [26], manufactured by SuitX for people with mobility disorders also falls under this category. This adjustable device is commercially available; for actuation it uses DC motors and has a battery life of 4 hours for powering purposes. Other exoskeletons like the Honda-leg, Keeogo, etc. are aimed also to compensate for some lost function in patients. Such compensation exoskeletons face major challenges of weight and cost reduction to make them popular among mass markets.

2.3 Non-Medical Exoskeletons

Non-medical exoskeletons are wearable personal care robots designed for various applications to assist healthy persons in carrying out some activity; examples include strength augmentation for workers to perform physically demanding tasks, for soldiers to carry heavy equipment and run rapidly over rough terrain and for helping healthy people carry out normal daily chores. The latter includes applications to support elderly in activities of daily living to allow them to stay active and independent with a good quality of life. General purpose exoskeletons have also developed in recent past which are used for multiple applications such as sports and recreation, for space scientists, etc. Non-medical exoskeletons can be further divided into four categories according to the need of the users and are explained next.

2.3.1 For Soldiers

Soldiers are fit/strong young persons who are expected to carry heavy equipment while marching at 6-10 km/hour for long distances and be fit enough to "fight" when they reach their destination. To assist in such cases military exoskeletons have been developed to amplify the capabilities of the soldier so that he/she feels only 5-10% of the actual load carried, so that long distances can be travelled with reduced metabolic costs. BLEEX (Berkley Lower Extremity EXoskeleton) [27] is one prominent system developed at University of California-Berkeley under a DARPA funded project to develop a versatile transport platform for mission-critical equipment. It comprises a portable power unit and uses linear hydraulic actuators to allow soldiers to carry around 100 kg without fatigue. Other similar military exoskeletons include Sarcos XOS2 [28], HULC [29], Exo-climber [30] etc. which have been designed to augment capabilities of soldiers in wartime and in emergency operations. The main challenge in developing load augmentation exoskeletons for soldiers is how to reduce the overall weight yet maintain high levels of augmentation for long durations so that soldiers will stay fresh for combat conditions. These devices are likely to be practically useful only if they reduce the metabolic cost significantly while augmenting the load carrying capacity of soldiers. Misalignment with the human joints during actuation is also another open research challenge for the future. Fig 2.5 shows soldiers successfully using exoskeletons during various operations on field.

Fig. 2.5: Soldiers using exoskeletons for weapon handling, for ammunition/equipment handling, and during running in natural terrain. [32, 33, 34]

2.3.2 For Workers

Workers in industrial environments have to perform physically demanding tasks which can lead to stress and adverse effects on health. Tasks can include lifting a heavy part for fitting on an assembly line or handling heavy equipment in pick and place operations. Exoskeletons have been designed to help workers in performing specialized motions by defining reachable spaces for the tasks to be carried out as shown in Fig. 2.6.

Fig. 2.6: Workers using exoskeletons in various industrial applications [35, 36, 37]

In this way the worker is supported specifically for 3D joint movements needed to be carried out, so that health is not compromised due to the nature of the physically demanding human motions in the work. In this respect, passive exoskeletons have also been realized, e.g. ROBOMATE [44]. Certainly, one can think why other types of robotized/ automation solutions are not used if the nature of work is not within human limits.

However, it is essential that human workers should not be replaced totally and good balanced approaches for developing collaborative human-robot solutions should be sought, by optimizing overall effectiveness of the final design. In this regard exoskeletons for physically supporting human workers, is an important research topic for the future.

2.3.3 For Healthy Persons (including elderly person applications)

This non-medical area of exoskeletons covers a wide area of users but one unique sector likely to grow in importance in the coming years is the support that wearable robots can provide to healthy elderly persons. Healthy elderly persons have no serious disability or disease as such, which demands intervention of medical personnel (except that they are old and their physical ability is reduced). Perhaps they are not as mobile as when they were younger or perhaps they get tired more quickly if significant physical effort is needed for some activity. This sector is often referred to as active assistive living (AAL) applications in Europe, [38] or the silver/graying society in Japan, etc.

Despite the global concern, only a few multi-purpose exoskeletons have been developed which can be used by elderly persons and no commercial exoskeleton is available to date. PhaseX [39], a spin-out company created by University of Gävle in Sweden aims to focus on developing and commercializing assistive exoskeletons classified as physical assistant robots in the recently published ISO 13482 [40] safety standard for personal care robots. Such wearable exoskeletons have the potential to meet the mobility requirements of healthy elderly persons for performing activities for daily living. The aim is to develop user-centric solutions to develop affordable mass market consumer products rather than high-value low volume systems.

2.3.4 For General Purpose

General purpose exoskeletons include all those wearable devices which are designed and manufactured with no specific target application. These are multi-application devices which can cater to different types of users e.g. for sports, recreation, astronauts, etc. Due to this reason, these exoskeletons are heavy and massive in size as they do not target any particular user. NASA's X1 [51] is an example of such a device which was developed by NASA and IHMC with many application areas including – assisting motion of astronauts in space/extra-terrestrial surfaces, walking of paraplegics, for exercising and other applications etc. General purpose exoskeletons are useful devices but cannot target mass markets, as they lack a dedicated design approach. Moreover, exclusive devices for specific application area are available these days, as already explained.

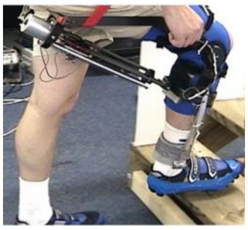
2.4 Comparison Table

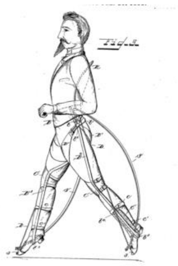
Table 2.1 has been developed to give an insight into the key features of wearable exoskeletons which includes mechanics (joint mechanisms, number of degrees of freedom, material, etc.), types of actuators used, control strategy, sensors deployed, battery life, etc.

Table 2.1 Comparison of lower limb exoskeletons

#	Exoskeleton	Category And Sub-Category	Weight (kgs)	Actuator	Key Points (Control, Sensors, Materials, Joint Mechanisms, Battery details)
1.	BLEEX [27] 	Non-Medical - Soldiers	14	Linear hydraulic Actuators	• Capable to carry 100 kg load • 7 DOFs • Designed for a 75 kg human • 1143 W hydraulic power for actuation • 200 W electric power for control • 8 encoders and 16 linear accelerometers for sensing position • 0.9 m/s with 75 kgs load and 1.3 m/s without load
2.	Sarcos XOS-2 [28] 	Non-Medical - Soldiers	95	Linear and Rotary hydraulic Actuators	• Capable to carry 84 kgs, 30 DOFs • Wearer's feet not allowed to bend • Multi-axis force-moment transducers for sensing and control • Strength ratio increase - 17:1 • 1.3 m/s with 68 Kgs on back • Able to walk through mud, twist, kneel and squat

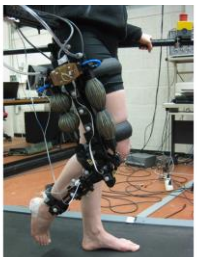
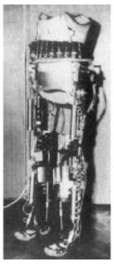
3.	Exo-Hiker [41] 	Non-Medical - Soldiers	14.5	Linear hydraulic actuators	• Capable to carry 90 kgs • On board computer, display and sensors • In-built solar panel for energy generation • Lithium polymer battery (80 W-h, 0.5 Kgs) • Quick emergency release option from the suit • 21 hours battery life
4.	Exo-Climber [30] 	Non-Medical - Soldiers	23	Linear hydraulic actuators	• Advanced version of Exo-Hiker for rapid climbing of stairs. • 90 Kgs payload capacity. • Small fuel cell as optional energy source. • Battery weight : 0.9 Kgs • Retractable legs for quick release
5.	NAEIES [42] 	Non-Medical - Soldiers	N. A.*	DC Motors with harmonic gear box	• Capable to carry 15 kgs load • Potentiometers and gas springs used as control elements • Aluminium used as base material • Adjustable according to user height • 6 DOFs • 1 hour battery life
6.	HULC [29] 	Non-Medical - Soldiers	24	Linear hydraulic actuators	• Capable to carry 90 kgs load • Titanium body, user adjustable • Lithium-polymer battery • Range: 20 km on level terrain at 4 km/hour • Put on-off time 30 seconds
7.	MIT Exoskeleton [43] 	Non-Medical - Soldiers	11.7	Quasi passive mechanism and variable dampers	• Capable to carry 36 kgs load • Magneto-rheological damper at knee joint. • Strain-gauges and potentiometers used as sensors. • 2 W electric power provided by a portable battery (48 V) in bag pack • Increases 10% metabolic cost

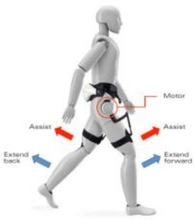
8.	Roboknee [45]  .	Non-Medical - Soldiers	N. A.	Linear Series Elastic Actuator	• User decides when and where to walk • Stair climbing possible • 4 kgs Nickel-Metal-Hydride batteries in bag pack • 1 DOF at knee only • 1 hour battery life • Actuator weight – 1.13 kgs
9.	Hardiman [46] 	Non-Medical - Workers	680	hydraulic Actuators	• Capable to carry load up to 750 kgs • External power source for hydraulics • 30 DOFs • Amplifies legs, arms and hands but not wrist • Strength ratio increase - 25:1 • Full body device never tested due to control problems
10.	PercRo Body Extender [47]  .	Non-Medical - Workers	160	DC brushed torque motor	• Used in material handling, industrial applications • Acts as load augmentation device • Each hand can lift 50 kgs each • External power via batteries • 22 DOFs • Amplification range : 3-20
11.	RB3D Hercule [48]  .	Non-Medical - Workers	30	Electrically powered motors	• Capable to carry 100 kgs load • Multipurpose exoskeleton • Lithium-ion rechargeable battery • 33000 USD cost • 4 hours battery life • Real-time management of movements via ARM Cortex-A8
12.	Fortis Exoskeleton [49]  .	Non-Medical - Workers	12.3	No actuator is used	• Unpowered device: Doesn't require external power, works on human power via links and mechanisms • Reduces muscle fatigue • Quick put-on and put-off (Less than 2 minutes) • With its tool arm the user can lift 16 kgs easily • Adjustable to different body types

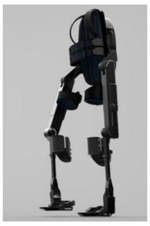
13.	Power Loader Light [50] 	Non-Medical - Workers	38	Carbon Fiber motor	• Developed by Panasonic & ActiveLink • Aluminium alloy frame • Designed to help workers lift and carry objects more easily and with less risk of Injury • Increases leg strength by 40 kgs • Reduces user fatigue and tiredness
14.	Yagn's Running Aid [51]  .	Non-Medical - General	N. A.	Springs, gas bags and links	• First patent of an exoskeleton like device, in 1890's • Never successfully demonstrated • Earlier version used long leaf springs • In improved version gas bags were used for storing energy • Designed to augment walking, running and jumping
15.	X1 Mina Exoskeleton [52]  .	Non-Medical - General	27	DC motors	• NASA and IHMC collaboration • Application in space crafts for astronauts and for paraplegics • Ensures better health of the user. • 10 DOFs • Safety system for overloading/overextension • Aluminum and carbon fiber used
16.	Ekso [13]  .	Medical - Paraplegics	20	Hydraulic actuators	• 6 DOFs • Adjustable assistance levels – 'Variable assist' • Peak torque of 150 Nm • Battery, computer and portable compressor in bag pack • Encoders and linear accelerometers used as sensors. • 100,000 USD cost • 6 hours battery life
17.	ReWalk [11] 	Medical - Paraplegics	15	DC motors	• Crutches needed • Control through wrist-pad controller • Speed up to 2.6 kmph • 70000 USD cost • 2 hours 40 minutes battery life

18.	Indego [12]
	
		Medical
		-
		Paraplegics
			12	DC brushless motors	• Can be split into 3 pieces and then coupled
					• Easy to wear and remove
					• Wireless operation
					• 140,000 USD cost
					• 1 hour battery life
					• 2 variants –
					  ○ Indego Personal
					  ○ Indego Therapy

19.	Rex [14] 	Medical - Paraplegics	38	Linear actuators	• No need of support stick • Joystick for control • Custom rechargeable battery (adds to the weight) • 150,000 USD cost • 2 hours battery life
20.	Atlante [15] 	Medical - Paraplegics	N. A.	Electric motors	• No use of crutches, joystick • 12 DOFs • Dynamic balancing control • R&D by Wander Craft Ltd. • Cost: 33000 USD • 3 hours battery life • Self-contained autonomous device
21.	University of Wisconsin Exoskeleton [53] 	Medical - Paraplegics	27.2	Rotary hydraulic actuators	• Universal Joints at hip/knee • 4 actuators (2 at knee, 2 at hip) • DC motor drives hydraulic pump • Off-board computer for control • Sticks needed for stability • Comfortable to the user for long duration wear
22.	Innophys [54] 	Non-Medical - Workers	5.5	Pneumatic Artificial Muscles. (McKibben type)	• 30 Kgs load capacity • Compressed air and battery used for power • Reduces the burden on spine and back. • 4970 USD cost • Aluminum body • Targeted on elderly workers

23.	LOPES [18] 	Medical - Rehabilitation	N. A.	Series Elastic Actuator	• Two modes- Robot and patient. • 8 DOFs. (3 at hip) • Treadmill device with Bowden cable system. • Impedance control strategy. • It is for treadmill training. • 8 DOFs. • It can move in parallel with the legs of a person walking on a treadmill.
24.	KNEXO [56] 	Medical - Rehabilitation	4.5	Pleated Pneumatic Artificial Muscles	• 1 DOF at knee joint • Uses external compressor • Supports up to 90Kgs person • A ‘zero torque’ mode for unassisted walking • Interaction based trajectory controller is used • Need of pressurized air makes it less mobile
25.	Nurse Power assist suit [25] 	Medical - Compensation	30	Pneumatic rotary actuators	• Helps the nurses to carry patients and heavy equipment in hospitals • Ni-Cd batteries used • Muscle hardness sensors used for control strategy • PWM and microcontrollers for torque control • 20 minutes battery life
26.	Exoskeleton Walking Aid [54] 	Medical - Compensation	16	Electric actuators	• 7 DOFs. (2 knees, 2 hips, 1 ankle, 2 torso frame) • 2 Kgs battery • Stability control with ZMP (Zero Moment Point) • Force sensors for feedback and control • Predetermined motion via ‘electronic diode’ • Also called Mihajlo Pupin Institute Exoskeleton • 45 minutes battery life
27.	Phoenix [26] 	Medical - Compensation	12.25	DC Motors	• Average speed: 0.5 m/s • Adjustable size according to user need • Comfortable to wear and remove • Cost: 40000 USD • 4 hours battery life

28.	HAL-ML05 Series [55] .	Medical - Compensation	12	DC Motors	• Capable to carry 40kgs load • EMG (myoelectric signals) used for control • Rotary encoders and strain gages used as sensors • Only exoskeleton to get global safety certification • Linux based computer system for parameter adjustment • 1950 per annum (Rent) • 160 min. battery life
29.	Honda Leg-Walk assist [56] .	Medical - Compensation	2.8	Brushless DC motors	• Lowers the strain of walking • Rechargeable Lithium ion battery • 2 DOFs, only at hip joint • For healthy elderly people. (which need only a few %age of assistance) • Other variants of Honda-leg include – Stride management and Body-weight support assist
30.	Wearable Walking Helper [57] .	Medical - Compensation	10	Linear actuator and DC motor	• Specific predefined movements • 8 DOFs (4 for each leg) • 128 Nm maximum torque • DC motor at hip joint • Gear drives used for transmission
31.	Tokyo Denki University Orthosis [58] .	Medical - Paraplegics	7	Bilateral hydraulic servo actuators	• Potentiometer for position control • Needs external hydraulic pump for power • Pressure sensors in shoes to maintain posture • 4 DOF per leg • Can also be used for gait training
32.	MindWalker [16] .	Medical - Paraplegics	30	Linear Electric actuators	• 5 DOF at each leg. • Works on user command • Centre of mass control strategy for walking • User needs to hold handrail for walking • Able to recover balance from external instability

33.	North-eastern University Orthosis [59]  .	Medical - Rehabilitation	N. A.	ERF Variable Damper	• Modification done to a commercial knee brace • Provides resistive torque to user for rehabilitation • Gives 30Nm torque (25% assistance) • Lightweight aluminum design • Can be used for other applications e.g. by astronauts
34.	Exo-H2 [60]  .	Medical - Paraplegics	12	DC Motors	• Adjustable control parameters according to patient needs • Needs support stick for autonomous walking by user • Lithium powered 22.5 V DC battery • Can be connected to mobile via Bluetooth for control • 6 hours battery backup
36.	AxoSuits [61]  .	Medical - Paraplegics	N. A.	Electric Actuators	• 6 hours battery life • Adjustable recovery settings • Adjustable size for various patient height and weight • Low power consumption • Compact batteries
38	Arke [62]  .	Medical - Compensation	N. A.	Not available	• Real-time data storage and display on cloud software • Carbon fiber, steel and aluminum used. • Fully customizable for weight and height • Novel walking gait trajectories • Cost effective and compact electronic system
39	Kawasaki Power Assist [63]  .	Non-Medical - Workers	N. A.	DC motors	• Load carrying capacity: 40 Kgs • Li-ion battery • 4 DC motors used • Wearer doesn’t even feel the weight of suit while moving • Less than 1 minute put on/off time

40	ExoAtlet [64] 	Medical - Paraplegics	N. A.	Electric actuators	• EMG and torque sensors for control • Support sticks needed • Bag-pack for battery • Climbing stairs possible • Can also be used for physiotherapy
41	NTU-LEE [65] 	Non-Medical - Soldiers	N. A.	DC motors	• Performance augmentation device for emergency personnel • Adjustable motion strategy • Gives 118 Nm torque output • Can also be used as aid for people with gait disorders • Adjustable shank and thigh length
42	HEXAR Exoskeleton [66] 	Non-Medical - Workers	21	Electric Motors	• 7 DOF for each leg • Gearing system for transmission • Quasi-passive mechanisms used • 5-6 hours battery backup • 1.5 Kmph with 40 kgs load
43	PhaseX [39] 	Non-Medical - Healthy elderly for daily living motions (balanced standing, sit-to-stand, walking)	N. A.	DC Motors	• 3 DOFs for each leg (hip, knee, ankle) with encoders • Pattern generator, harmonized controller • Speed 30 steps/min • For home use where charging sockets exist in all rooms • Material – aluminium with plastic covers

2.5 Summary

The points discussed in the literature survey and the comparison table includes all the relevant issues which play a role during design and development of an exoskeleton device. The problem formulation for this thesis work is mainly focussed on the common limitations highlighted during this literature survey and comparison work. The problem formulation is discussed in the next chapter in detail.

Chapter 3

Towards CVT-based Torque Variation Method

3.1 Literature Gaps

After having a closer look at the comparison table, the significant literature gaps and the major problems faced by lower-limb exoskeletons are highlighted and further investigated. These are mentioned below:

- The key component in wearable exoskeletons is the actuator. It is the powerhouse which gives of the ability of motion. Many types of actuators are used in exoskeletons depending on application, e.g. heavy hydraulic actuators are used in military applications to provide huge augmentation capabilities to soldiers, and light/ compact actuators are preferred in medical applications where patients are not able to carry large/heavy weights. Compact actuators are costly and cheap ones are bulky and also less efficient. Better and more appropriate actuators which are lighter, more compact, safer yet are affordable is the main open problem needing attention by the research community. Whether the current actuators provide sufficient clarity and focus on what is needed for supporting the motion of human joints is also worth exploring. For example, current electrical motors tend to be focused on providing very tight positioning control capabilities whereas for supporting human motion applications such level of precision is not the most important issue. Developing more appropriate motors for wearable exoskeletons must be explored as a matter of urgency.
- The performance of actuator depends on the control strategy adopted to provide the required power at individual joints for the specific motion being performed. Various control strategies have their own pros and cons. For example EMG control is not totally reliable due to errors in sensing the muscle movement and mismatch with wearer’s intentions. Fixed trajectory control methods face problems of synchronization they can disturb the natural gait cycle. Fully efficient and robust control strategies for specific human motions for mobility functionalities are still missing. The area must be explored and a range of sensory

interfaces deploying multiple sensors and diversity explored to realize the advances needed

- Long term power supplies to provide energy for the actuators is also a major issue in making the exoskeleton fully autonomous for long periods. As electric actuators are widely used, batteries used for powering them need to be improved. Most batteries have problem of weight, limited life spans, limited number of charge/discharge cycles, etc. This poses a great challenge for researchers to develop lighter, denser and longer lasting battery technologies.
- Other factors, like more lightweight materials with the needed strength for making exoskeleton structures, better sensors to detect variety of human motion intention, and more miniaturized electronics to reduce overall size and weight of the exoskeletons.
- Safety is the major concern of the governmental and regulatory organizations before allowing new products to be commercially available to the public. In this regard, only a few exoskeletons like the ones from Rewalk, Ekso Bionics, and Cyberdyne have been certified to comply with the new emerging international safety requirements in medical and non-medical applications. This is a major concern as it affects the widespread commercialisation and opening up of new exoskeletons markets globally. Consumer's and patient's trust and confidence is heavily dependent on international safety standards and use of widely recognized certification processes. For eradicating all such problems, the regulatory issues are discussed in detail in next subsection.

3.2 Regulatory Issues

In emerging domains such as exoskeletons, it is important to not just focus on developing technology and prototypes for testing in research labs but have a clear vision for how the advances can make real impacts in society. In this regard, how wearable exoskeleton markets can be created should be focused upon so stakeholders are aware of the issues needing attention. In this section, an overview is given to the international regulations which have a great impact on the design and development of the exoskeleton devices, in this case lower-limb exoskeletons for healthy elderly.

Governments have the responsibility to ensure that products sold in their territories are acceptable and meet the consumer requirements. For this purpose, governments adopt appropriate laws to ensure that the objectives are met and product safety is the primary goal so that harm cannot be caused to citizens by unsafe products being sold. When commercialization involves technical products, it is important to have in place a technical regulatory framework, where the regional authority makes the legislation that can apply to all levels of governments (national, provincial, state, municipal etc.) and covers product services and actions so that provisions (mandatory or not) can be put into place over and above the free market system.

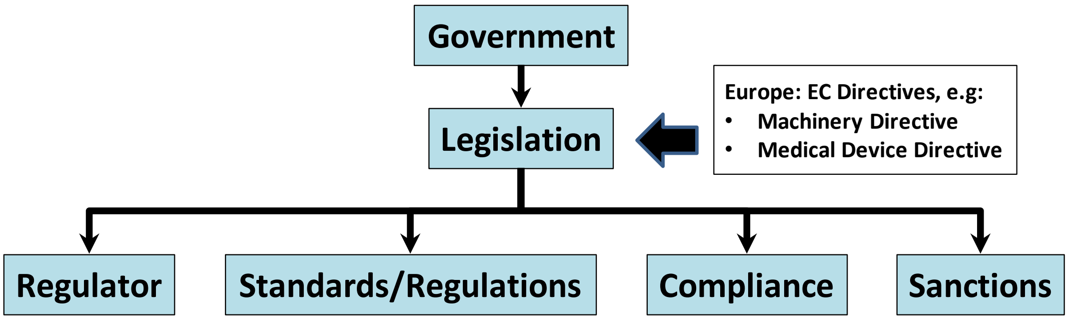


Fig. 3.1: A typical model of a regulatory system

Fig. 3.1 shows a typical regulatory framework so that technology is adopted appropriately in products, and the safety of its citizens is guaranteed. The key elements within such a technical regulatory system are the following:

- **Regulator:** must be established by law and must be a legal persona “juristic person” in the country. The powers of the regulator must be made known (as well as the limitations), and these must not have conflicts of interest with standards or conformity assessment bodies
- **Standards/Regulations:** standards are voluntary, but can be referred to or incorporated in regulations (which are the mandatory laws/rules in a country). There are a variety of standards resulting from international, regional, national, and even private initiatives and activities. They are produced and adopted for specific purposes, but international standards produced by ISO (International Organization for Standardization; www.iso.org) and IEC ((International Electro-technical Commission; www.iec.ch) have the strongest presence as they consist of international networks of national standards bodies which represent the majority of stakeholders in each country, from all regions of the world, working in partnership with international organizations such as the United Nations, its specialized

agencies and the World Trade Organization (WTO). The fundamental basis of developing international standards is that they are globally acceptable, is that they must involve a public inquiry phase, allowing all stakeholders to be involved, and they must be based on consensus. Once such international standards (as well as other relevant information) are available, it is the regulators who set the legal regulations based on information gathered by public enquiry, and these regulations are backed by government.

- **Compliance:** Conformity assessment to the regulations should uphold international principles and use accredited service providers. The use of mutual recognition agreements are recommended as are third party independent organizations which respect WTO rules in a transparent manner
- **Sanctions:** For the regulatory system to work well, the regulator's powers are normally well defined in detail in terms of entry of premises, samples to be tested, what can be confiscated and disposed off, what fines can be imposed, suspension and prohibitions of trading, etc.

Hence, the role of robot standardization is to support such technical regulation by ensuring robot products are safe, reliable, and of sufficient quality to work as intended, through clear and unambiguous provisions agreed to by all the relevant stakeholders in order to facilitate trade and communication. By having international standards, it is possible for the companies to sell their products anywhere they want because they contain all the information needed about differences between individual countries they want to export to. By using an International standard, a company loses less time (and uses less resources), and is able to produce products that operate in a predictable way anywhere in the world.

For example, in Europe a number of EC Directives have been adopted as law and two such directives relevant to the exoskeletons being discussed here are the following:

- **Directive 2006/42/EC:** Machinery Directive. [67] This is written to promote the design of machinery that is as safe as possible according with the current status of technological development. This directive applies to machines generally defined as devices with at least one moving part, containing actuators, control, and power circuits. Exceptions to the Machinery Directive exist and are normally covered by other regulations, as well as machines in which the main risk is of electrical origin (in which case only the Low Voltage Directive would apply). Machines with increased risk (due to high power, mass, speed, etc.) must be certified by a notified body. Most robots to date have been classified as machines and hence the robot safety standards need to comply with this directive.

- **Directive 2001/104/EC:** Medical Device Directive. [68] The key issues in the definition of a medical device are the following: any instrument, apparatus, appliance, software, material or other article, whether used alone or in combination, together with any accessories, including the software intended by its manufacturer to be used specifically for diagnostic and/or therapeutic purposes and necessary for its proper application, intended by the manufacturer to be used for human beings for the purpose of: 1) diagnosis, prevention, monitoring, treatment or alleviation of disease, 2) diagnosis, monitoring, treatment, alleviation of or compensation for an injury or handicap, 3) investigation, replacement or modification of the anatomy or of a physiological process, and which does not achieve its principal intended action in or on the human body by pharmacological, immunological or metabolic means, but which may be assisted in its function by such means. These issues are important and hence any robot designed to meet a medical need must be regulated as a medical device (under this medical directive) rather than as a machine (under the machine directive).

When focusing on the ageing society problem, exoskeletons complying with both machinery and medical device regulations are needed as discussed in this paper. The former exoskeletons are for healthy elderly persons (customers) who just need help to continue living in their own homes for as long as possible, whereas the medical exoskeletons are for patients with specific medical issues where medical consultation is needed and the appropriate medical aids need to be prescribed by medical professionals.

Before going in the details of the machinery and medical issues for robots, it is worth noting that, prior to 2005, the main robot standardization work was carried out by ISO for only industrial robots complying with safety requirements for machines. These industrial robots were (and still are) powerful and dangerous machines and hence the requirements (published in ISO 10218-1, -2 [69]) relied upon keeping humans and robots separated by the use of real or virtual work cells with physical barriers to automatically apply safety interlocks to turn power off to the robot if a human enters the robot's operational workspace. With the emergence of service robots (which includes exoskeleton robots), it was not possible to develop the needed robots since they demand close human-robot interaction for providing the "service" and new safety requirements have been published for personal care robots in ISO 13482. The service robot safety standardization efforts has also initiated consideration of robots as medical devices (known formally as medical electrical equipment) and requirements for basic safety and essential performance are being produced by a joint working group under IEC SC62D and ISO TC299. Brief summaries of the standardization work in the machinery and medical application sectors are presented in the next sub-sections as knowledge of this is essential to appreciate what is needed for wearable exoskeletons to be commercialized in these sectors.

3.2.1 Standardization of Exoskeletons as Machines

It is important to have an appreciation of traditional robot safety from its industrial manufacturing roots, where robots are powerful machines and the design has been based on keeping the industrial robots and humans separated by real or virtual cages to prevent harm to the humans as already stated. The industrial robot safety requirements are published in ISO 10218-1, 2. Since the late 1990s, as service robots have evolved, it has become clear that this "separation" philosophy cannot deliver the needed new robots and close human-robot collaboration is essential for service robots. And of course for exoskeletons, the robot is designed to be physically attached to a human during normal intended use. For this to be possible, new international robot safety requirements were needed and the important work to identify the new safety requirements was started in 2006 for personal care robots and has recently resulted in the publication of ISO 13482. In the course of developing ISO 13482, a number of key steps have been taken by the international robot standardization community. Some of these are the following:

- The definition of the term "robot" has been updated to programmed actuated mechanism with a degree of autonomy, moving within its environment, to perform intended tasks
- A new term "autonomy" has been defined as the ability to perform the intended tasks based on current state and sensing, without human intervention

- New types of robots have been defined as follows:
    - Service robot: robot that perform useful tasks for humans or equipment excluding industrial automation applications
    - Personal care robot: service robot that performs actions contributing directly towards improvement in the quality of life of humans, excluding medical applications
    - Physical assistant robot: personal care robot that physically assists a user to perform required tasks by providing supplementation or augmentation of personal capabilities
    - Medical robot: robot intended to be used as medical electrical equipment or as a medical electrical system

Hence wearable exoskeletons as discussed here are physical assistant robots as defined in the new terminology and ISO 13482 has developed the needed safety requirements using the well accepted risk assessment and risk reduction principles presented in the Type A standard (ISO 12100 [70]) via the three step method, namely:

1. try to achieve the safety requirements by means of inherently safe design measures
2. if inherently safe designs are not possible, then try to achieve the requirements by means of safeguarding or complementary protective measures
3. if neither of these solutions are possible, then provide information for use to the operator (warnings, instructions) to assist the operator in achieving acceptable safety

These steps ensure the risk is reduced to an acceptable level and, if this is not possible, the machine (exoskeleton) should not be used. The generic methodology has been used to identify hazards for personal care robots scenarios. The list of hazards presented is extensive and the most relevant hazards for wearable exoskeletons are likely to be the associated with the following:

- uncontrolled release of stored energy
- power failure or shutdown
- hazards due to shape of exoskeleton
- hazardous vibrations
- extreme temperatures
- hazards due to stress, posture and usage

- hazards due to exoskeleton motion
- mechanical instability generally and while carrying loads
- instability in case of collision
- instability while donning/ doffing exoskeleton
- hazardous physical contacts (to exoskeleton and to moving parts)

ISO 13482 has introduced low and general risk types of personal care robots. For exoskeletons, the low risk type is defined as "where low powered physical assistance is provided and the user can overpower the exoskeleton if needed in a single fault condition". In this way, design issues can be simplified yet the mandatory safety requirements maintained by the wearer being able to resist many hazardous situations. In commercialization and opening new markets, this could be valuable so that experience can be gained and priority areas identified for focusing further research advances, e.g., developing better sensors and actuators and more ergonomic controllers.

3.2.2 Standardization of Exoskeletons as Medical Electrical Equipment

When exoskeletons are discussed, especially for elderly persons it is clear, that medical applications (including aids for the disabled) need to be addressed because ageing often involve medical complications and hence medical consultation is needed. The standardization work has been started jointly by ISO and IEC, and, although the work is in its initial stages, it is clear that some exoskeleton robots will be classified and regulated as medical devices rather than as machines. This poses an interesting boundary question being pondered by the international community because it will lead to different regulation requirements. The issue is how the boundary between medical and non-medical wearable exoskeletons can be defined. For example, exoskeletons can be used for rehabilitation of injured persons (which is clearly a medical application) as well as physically helping a healthy person to carry a heavy load (clearly a non-medical application) but there are applications that are not so clear, namely an assistive exoskeleton for helping the mobility of healthy elderly persons. In non-medical applications, the user is referred to as a "normal person" (consumer) whereas in medical applications the term "patient" is defined as "living being (person or animal) undergoing a medical, surgical or dental procedure" and used to carry out the risk management process. Discussion is still needed to reach consensus on how the boundary will be defined and when a "consumer" for non-medical exoskeletons becomes a "patient" for medical exoskeletons.

When it comes to medical device regulation, IEC under TC 62 (Electrical equipment in medical practice [71]) has developed a general standard IEC 60601-1, 8 collateral and over 50 particular standards which cover the medical equipment domain in a comprehensive manner; the family of standards also includes 80601 standards when the work is carried out jointly within ISO. The collateral standards apply to all types of medical equipment issues of electromagnetic disturbances, radiation protection, usability, alarms, environmentally conscious design, physiologic closed-loop controllers, home healthcare environment, and emergency medical services environment. The particular standards apply to specific types of medical equipment such as cardiac defibrillators, nerve and muscle stimulators, etc. New particular standards for medical robots (80601-2-77 for surgery and 80601-2-78 for rehabilitation, compensation or alleviation of disease, injury or disability) are currently being developed and are expected to be published in late 2018/ early 2019. The 80601-2-78 applies to medical exoskeletons and is discussed further later.

The key regulatory process to follow for designing medical devices is the application of risk management presented in ISO 14971 [72]. Here it is not that risk should be reduced to "an acceptable level" under a single fault condition but it is important to focus on managing the risk by performing a risk-benefit analysis for the patient. This is because it is sometimes necessary to cause "harm" to a patient in the short term to treat them, e.g., perform surgical cuts to carry out the needed surgery. The requirements for medical devices cover basic safety and essential performance. Hence medical equipment need to perform the risk-benefit analysis for the patient to ensure basic safety which is along the lines of the machine regulations as well as ensure the essential clinical functionality is maintained. This needs to be stated by the manufacturer when the risk management file is prepared.

Work has been recently commenced to develop a particular standard IEC 80601-2-78 for medical robots for rehabilitation, compensation or alleviation of disease, injury or disability related to the patient's movement functions following any impairment. This covers exoskeletons for medical applications and some key definitions are being formulated. The status of some of these is as follows:

- actuated applied part: applied part that is intended to provide actively controlled physical interactions with the patient related to the patient’s movement functions needed to perform a clinical function of a RACA robot (see below)
- alleviation: mitigation of patient symptoms following an impairment
- assessment: procedure intended to qualify or quantify the level of impairment of a patient
- compensation: improvement of functioning following an impairment by replacement or support of body structures or body functions
- impairment: problem in body function or body structure such as an anomaly, defect, loss or other significant abnormality
- movement functions: collection of sensory and neuro-musculoskeletal and movement-related body functions that comprise human motor control
- Rehabilitation, Assessment, Compensation and Alleviation Robot (RACA): medical robot intended to perform rehabilitation, assessment, compensation or alleviation comprising an actuated applied part
- Rehabilitation: improvement of functioning of the patient following impairment by physical therapy

These terms clearly indicate the important issues that need to be addressed in designing and developing exoskeletons for medical applications and how the impairment should be treated in the medical sense. The work is continuing and updating the risk management process in this particular application of medical exoskeletons.

3.3 Torque Variation Methods

The issues addressed in this thesis work are the powering and the torque variation methods. The powering issue includes an alternate power source instead of DC battery, so that the user can wear the device for longer periods. For this purpose human powered products are incorporated like hand crank generators and rocking chairs which can harness human power and convert it into electrical energy for further use in exoskeleton device. This area is addressed by other group members, but the focus area of the author is torque control and variation methods. Till now mostly microcontrollers were used for torque variation in exoskeletons. Taking observations from the exoskeleton literature survey and looking at the overall improvement areas, investigation in following areas is started. These are also explained diagrammatically in Fig. 3.2 in form of block diagram.

1. To find an alternative source of battery charging
2. To find a suitable device for torque variation

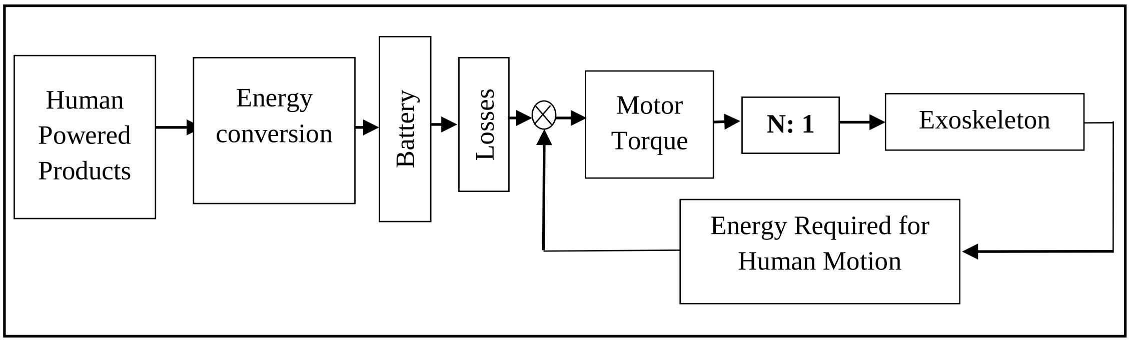


Fig. 3.2: Problem flow chart

Wearable exoskeletons require actuators to drive the various joints to give the needed motion to limbs; for example rotary or linear electrical motors, hydraulic/pneumatic cylinders are commonly used. The actuators normally provide constant operational speed whereas the motion requirement of human limbs varies for the different motions such as sit-to-stand, walking on flat ground or for stair climbing. Thus, a speed/torque control system is used which allows the appropriate toque to be applied at the required time. The most commonly used methods are presented in Fig. 3.3 with some issues which are relevant for wearable exoskeletons. Torque variation is of utmost importance in exoskeletons because user wants different speeds/torque for different operations e.g. walking, standing, sitting etc. For this a new device is needed which can save the motor power and also provide required torque and required time. Devices used till now are very costly and add to the overall cost of the exoskeleton. Devices used till now include gear drives [74], which is a completely mechanical device and is mostly used in load augmentation exoskeletons because it cannot be used in lower limb exoskeletons due to size constraint. Harmonic drives [75] are judged to be best devices for torque control but they are very costly and used only in costly exoskeletons, hence not useful for low-tech devices.

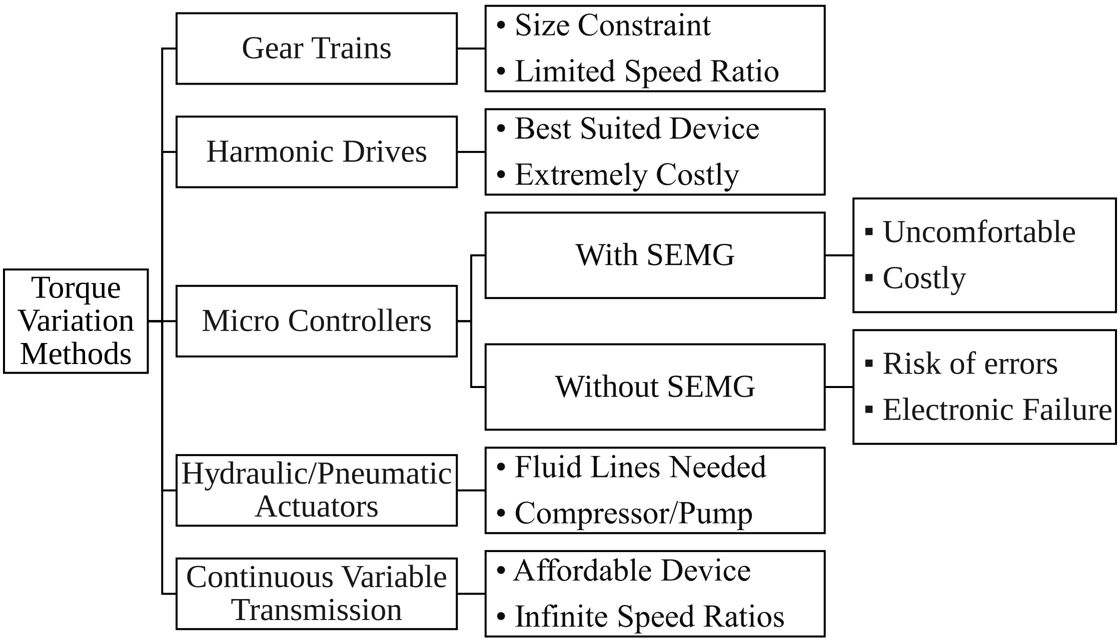


Fig. 3.3: Torque variation methods

Microcontrollers [76] seem to be a good option but its control strategies and failure problems make it a risky device for a stable device. Also it has sEMG (surface electromyography) which is uncomfortable for the user [46]. Hydraulic and pneumatics [77] is also used because of its high power benefits but it is limited only to military applications. The other most popularly used device continuously variable transmission or commonly called CVT [78] if miniaturised can be used in exoskeletons. It can be seen clearly from the comparison that continuous variable transmissions offer a good potential approach. So it is further explored in the next chapter and its feasibility for exoskeletons is done.

3.4 Summary

In this chapter, literature gaps are discussed some of which are addressed in this thesis in next chapters. Then, the regulatory issues related to exoskeleton devices are discussed which play a vital role in designing of the exoskeleton. The various torque variation methods which are employed in exoskeletons are discussed in detail and comparison is made to select the most suitable torque variation method, which is explained in the next chapter.

Chapter 4

Continuous Variable Transmission (CVT)

4.1 Introduction

The Continuously Variable Transmission (CVT) is an automatic transmission system, which changes the diameters of input shaft and output shaft directly instead of going through several gears to perform gear ratio change. This design can generate an infinite number of possible gear ratios. Fig. 4.1 below classifies CVTs in a broad way.

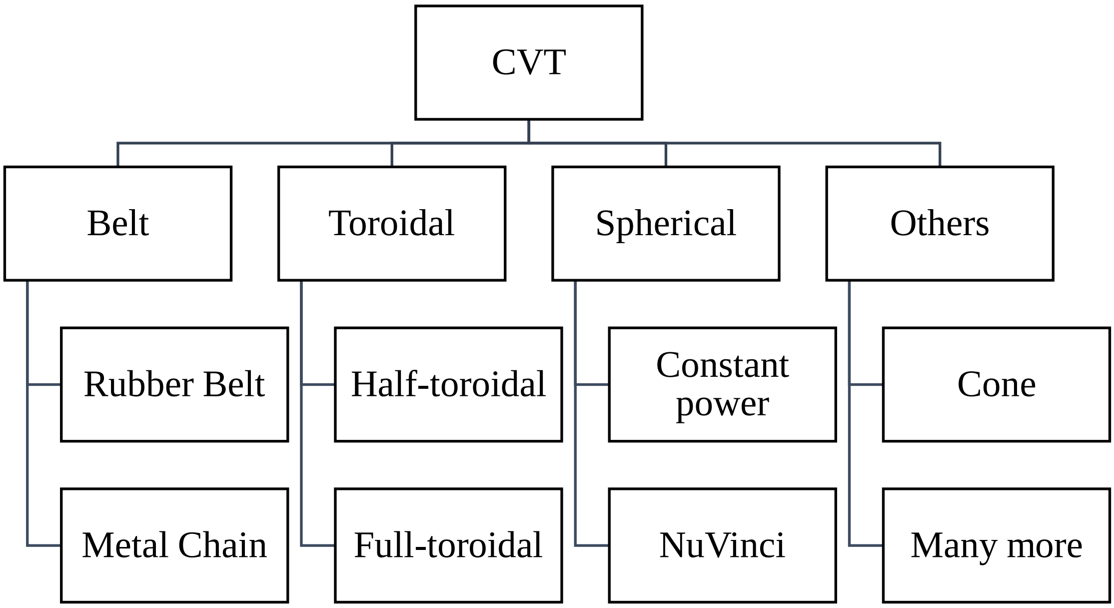


Fig. 4.1: CVT Classification

4.2 Belt CVT

The belt based CVT [79], or also known as Van Doorne System is the most common Continuously Variable Transmission. The divergence of two cones of the drive pulley cause a decrease of its diameter and the gear is high, as shown in fig. 4.2 (a). While they are getting close, the driven pulley's diameter becomes large and the gear gets low. Friction between the cones and the belt causes the transmission motion. This is based on the system of a Variator, which means a change in the ratio cause a change in the transmission. The basic idea using friction to transfer energy causes an extremely large stress on the belt where it has contact to the cone. While constant spinning the belt gets worn.

So, the system is still effective for small engine vehicles under 1,500 cc, like the drilling machines, mentioned before. So, it only could be realized in cars with engines of 1.2 liters or less, where not as much is derived from the system. Continuously Variable Transmission avoids the power loss caused by pushing the clutch to change gear. This system has been successfully used in other areas of motor driven machines, like drilling machines. It also needs less individual components for its functionality than a manual transmission. Less used parts means a less complicated system.

Metal chain belt CVT, as shown in Fig. 4.2 (b) also have same working but it consists of metal chain instead of rubber belt which means it is used for high power transmission e.g. in trucks and heavy duty vehicles. Belt CVT when looked at in perspective of exoskeletons, gives us an idea that if successfully belt can be miniaturized it can be useful for exoskeletons but the sheave control mechanism needs to be installed separately, that on a very space scarce joint e.g. knee joint. So, authors moved on further to other types of CVTs because apart from miniaturizing problem the shave control becomes a big problem, which needs its own motor and control mechanism, which will become difficult.

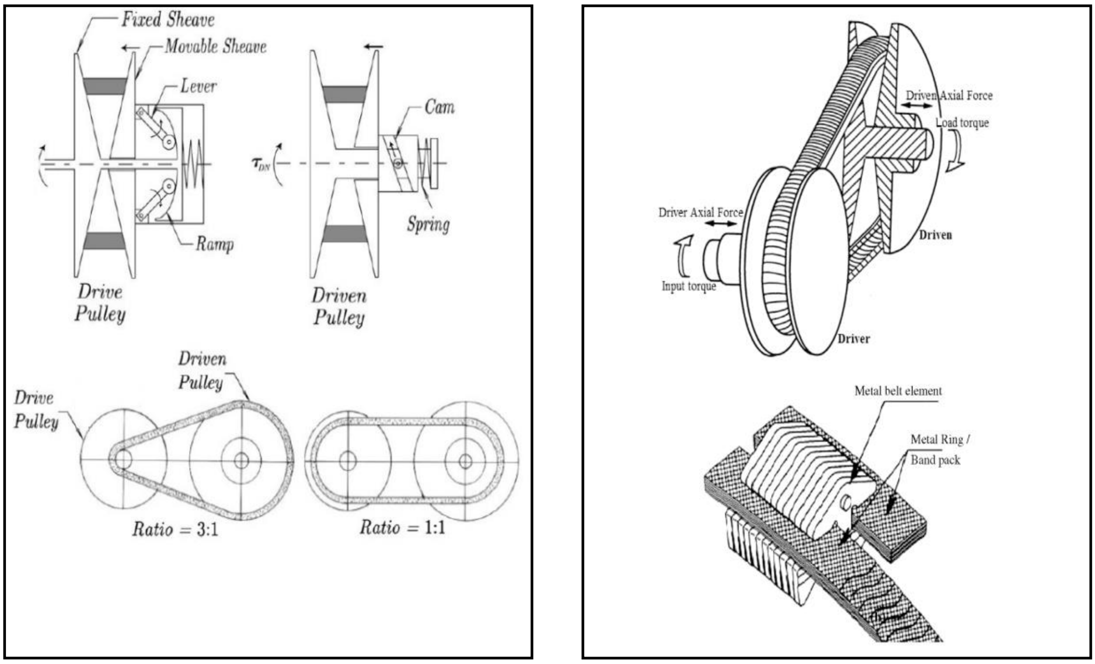


Fig. 4.2: (a) Rubber belt CVT [79], (b) Metal chain CVT [80]

4.3 Toroidal CVT

Roller based CVT is also known as toroidal CVT [81]. Here, rollers transmit power of engine between the discs. These discs can be seen as two conical parts. The contact between the rollers and those cones are point to point. One disc is connected to the engine, which is the input or driving part and the other one is the driven part. The rollers transmit the power from the driving part to the driven part. Changing the angle of the rollers will cause the transmission, as the ratio of the diameters change. The point to point contact between rollers and cones are based on rolling traction. The cones have to be tilt to change transmission ratio and it is not an easy system to control.

Until now there are problems according to the high production costs and the weight of this system. Additionally the contacts are based on friction and the contact liquid between is oil. During the driving process high temperature occurs in a car and the oil reacts differently when it gets heat up. So this influences the performance of the CVT unexpectedly. Also this system provides a constant connection to the engine's power, because it has an infinite number of gears and needs no clutch. In conclusion this system also has not been technically matured because the advantage of infinite numbers of gears cannot compensate the loss of effectiveness because of its slow reaction when the gear change is performed.

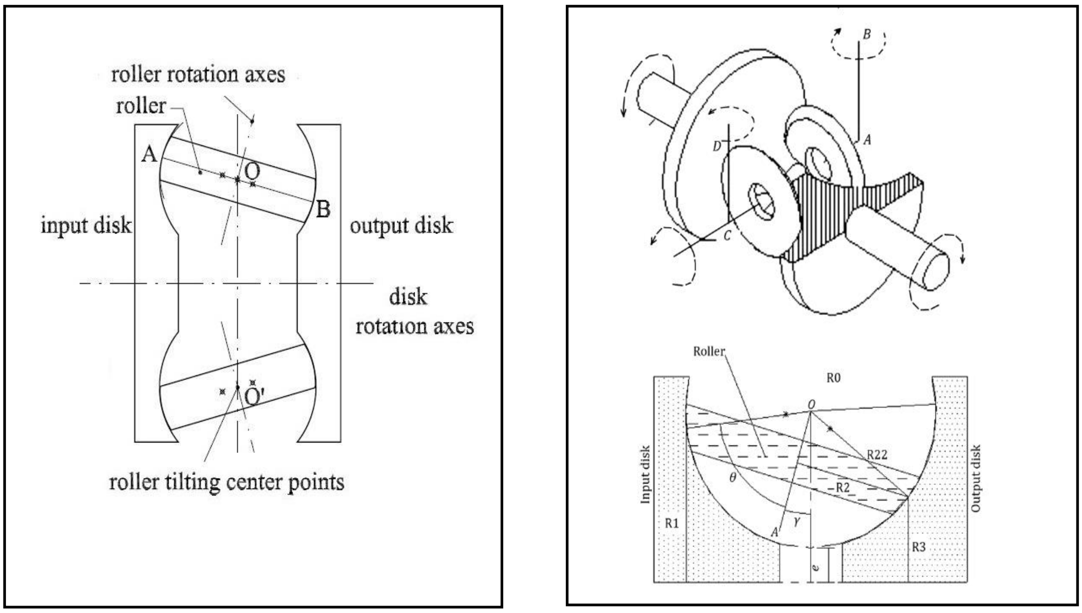


Fig. 4.3: (a) Half-toroidal [81], (b) Full Toroidal CVT [82]

Fig. 4.3 shows a half and full toroidal CVT, the operation of half and full toroidal CVT is quite same just the speed ratio is different and in half toroidal the torus is only half and in full toroidal the roller can move in a full torus. With respect to exoskeletons, this device has two major problems, first is the low speed ratio of the order 0.5-2.5 the other is the bulky structure which increases the volume of the actuation system installed on a joint, so not aesthetically and ergonomically a good device. Moreover, the need of traction fluid becomes a problem which gets heated up and can be uncomfortable for the user who is already elder.

4.4 Spherical CVT

Spherical CVT [86] is a CVT in which metal sphere balls are used to vary the speed ratio by varying their effective contact distance. The constant power spherical CVT, also called the CP-CVT [83] is a type of spherical CVT, the device consists of two input discs, one conical, fixed to the shaft and the other toroidal, which has axial but not rotational mobility relative to the shaft.

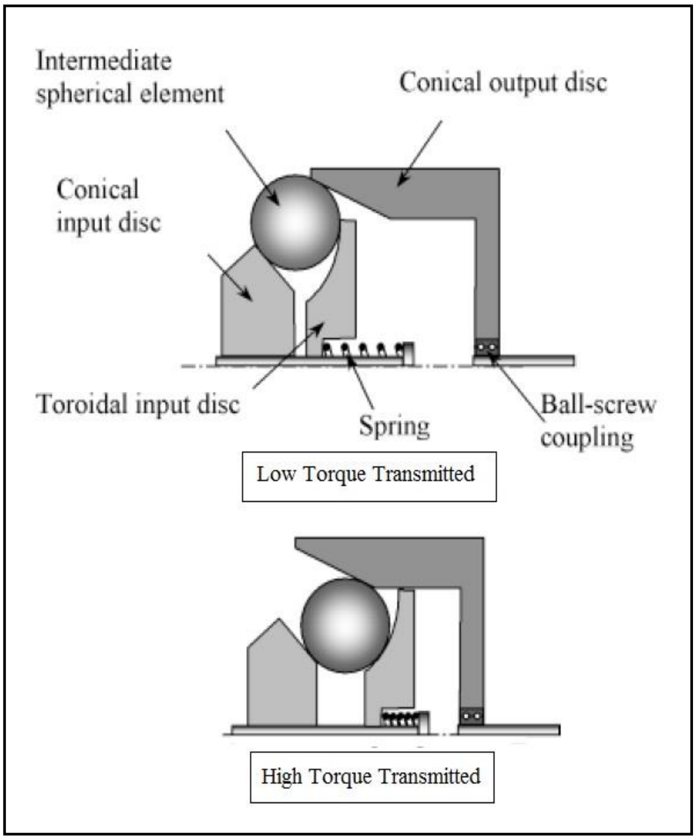


Fig. 4.4: Constant power CVT [83]

An inverted conical output disc is connected to the output shaft through a mechanism which is able to convert torque to axial force, such as a ball-screw. Between the input and output discs there are placed a convenient number (typically three-five) of spherical elements, which do not have a materialized axis of rotation. The arrangement of these parts is shown in Fig. 4.4. A resistive torque (T) applied to the output shaft causes the output disc to move axially, forcing the balls to change their position relative to the input shaft, thus changing the position of the contact points on each ball element. This will cause a change of the transmission ratio, the degree of which will vary depending on the geometry of the elements. The force produced by the ball screw coupling is balanced by a force applied to the toroidal disc (FA), which also serves to load the contacts allowing traction to develop between elements. This force is provided by a carefully designed loading system, which in the simplest case can be linear with respect to toroidal disc displacement by use of a disc or coil spring.

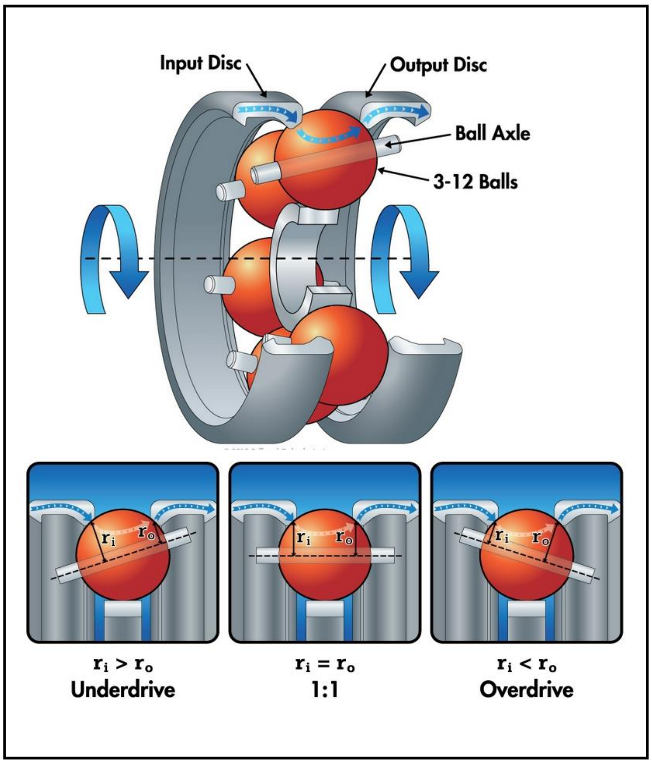


Fig. 4.5: NuVinci [84]

The balance of this force and the force produced by the ball-screw coupling means the CP-CVT is able to automatically adjust the transmission ratio to overcome any torque applied to the output, providing a potentially constant-power output. A ball separator or cage (shown) is also required to ensure the spherical elements rotate about their own axis and do not contact one another. The separator shown in the figure is perhaps the simplest possible design.

In exoskeletons, again the problem of the position control of sphere and cone becomes a problem, because even this is a constant power device, can be converted to torque variator but needs high precision in sphere control and positioning which will become a disadvantage in exoskeleton because it is not a stationary device, the user have to wear it and walk, hence increases the possibility of error. The other spherical CVT is NuVinci [84], which is a patent and a commercial device. The constructional features and an outlook of NuVinci is shown in fig. 4.5 which uses very simple principle of a spherical ball control which changes the output gear ratio, here also control is a big hindrance.

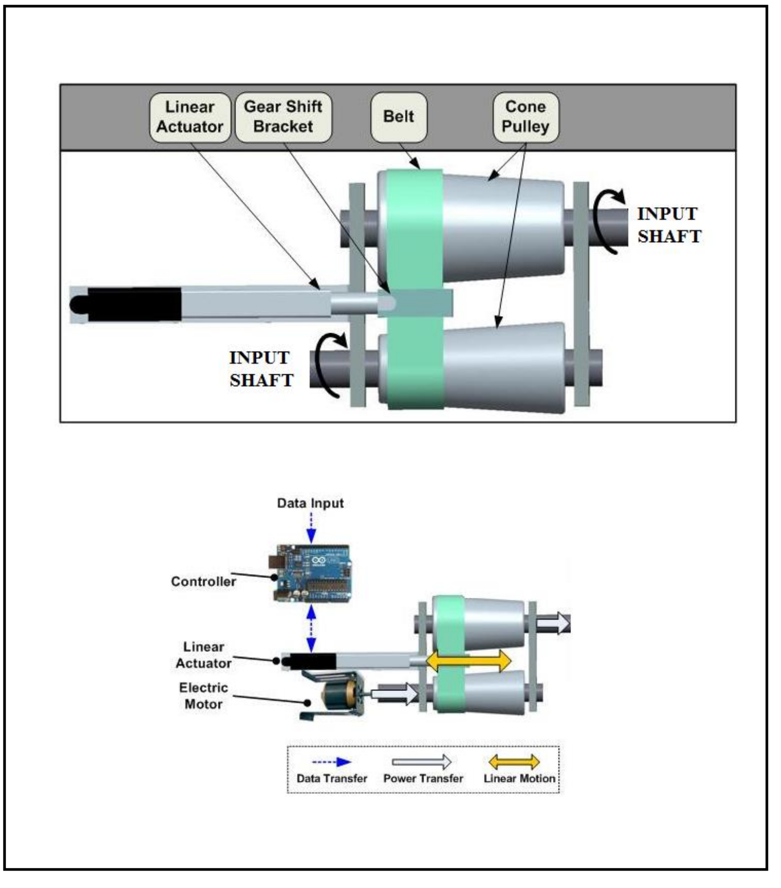


Fig. 4.6: Cone CVT [85]

4.5 Other Methods

There are many other types of CVTs, which are not commercial yet or are still in research stage. Cone CVT [85] is also a CVT which is not very popular. The schematic diagram of cone CVT is shown in Fig. 4.8, which clearly explains its principle. The change in lever position changes the gear ratio. Lever position is further controlled by a programmable microcontroller which can be programmed according to the need of the device, on which cone CVT is installed.

4.6 Summary

Table 4.1 briefly summarizes the above discussion on CVTs and its application in exoskeletons. From the table, it is apparent that the cone CVT is a good option for deployment in wearable exoskeletons and should be further explored. Cone CVTs are used with a linear actuator, operated with a controller and a linear actuation mechanism [85] to obtain infinite speed ratios.

Table 4.1: Comparison of different CVTs

CVT Type	**Speed Ratio Range**	**Observations**
Belt CVT [80]	*0.5-2*	• Small speed ratio range • Difficult to miniaturize
Toroidal CVT [81]	*0.5-2.5*	• Complex torus and roller design • Difficult control strategy
Spherical CVT [86]	*0.2-3*	• Problem of slippage • Traction fluid needed
Cone CVT [85]	*0.1-4*	• Easy to design and miniaturize • Cost-effective and low number of parts

For exoskeletons, finite speed ratios are sufficient but a large speed ratio is required, which has driven us to use a step cone CVT for realizing the solution needed in an affordable technical design. In this respect, a step cone CVT is considered and optimized in next chapter.

Chapter 5

Optimization of a Step Cone CVT

5.1 Introduction

The exoskeleton made by the Swedish group called as PhaseX, which is under experimental stage at University of Gävle (SWEDEN) as shown in Fig. 5.1. Alternate torque variation technique is to be used in this exoskeleton, for which following optimization study is conducted. The exoskeleton is being developed for healthy elderly for daily living motions for balanced standing, sit-to-stand and walking operations. The weight of the device is near about 28-30 kgs. It has 3 DOFs for each leg for each joint i.e. hip, knee and ankle. At each joint, an electric motor is used with encoders. At knee joint, Maxon motor (100 W) is used, whose parameters are used for the optimization study in this chapter. The exoskeleton employs a pattern generator and harmonized controller also. Its speed is 30 steps/min. The material of the device is aluminum with plastic covers which are made using 3D printing. In this chapter, a step cone CVT is realized to alter torque at the knee joint of the exoskeleton.

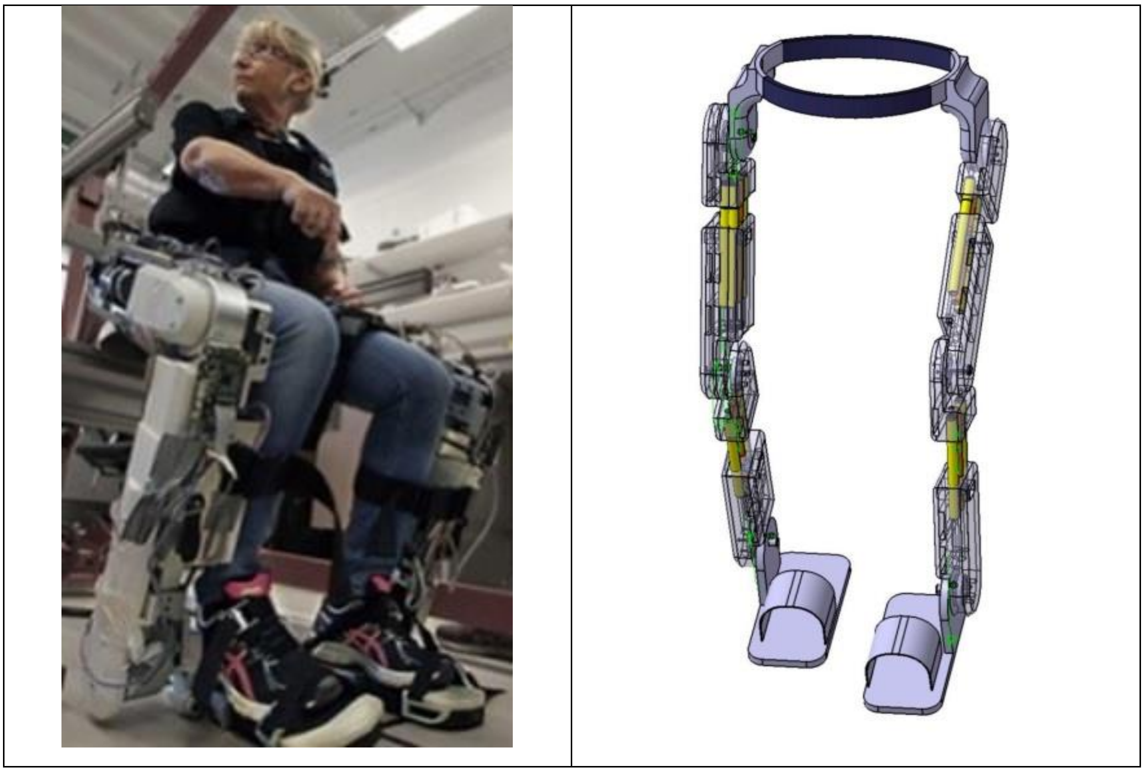


Fig. 5.1: Actual photograph and CAD model of initial design of PhaseX [39]

As discussed in Chapter 4, step cone CVT is the only feasible methods of torque variation which can be further explored for use in exoskeleton for healthy elderly. A three step cone CVT as shown in Fig. 5.2 is used which will give the user three speed options (low, medium and high), speed steps can also be increased to four or five depending on the requirement, but initially a three step cone CVT is considered. The objective is to optimize a three-step cone CVT which has four design variables i.e. the diameters of the three steps and the width of each step which has to accommodate the belt drive. A three step cone CVT is shown in Fig. 5.2 and it is assumed that the widths of steps are the same.

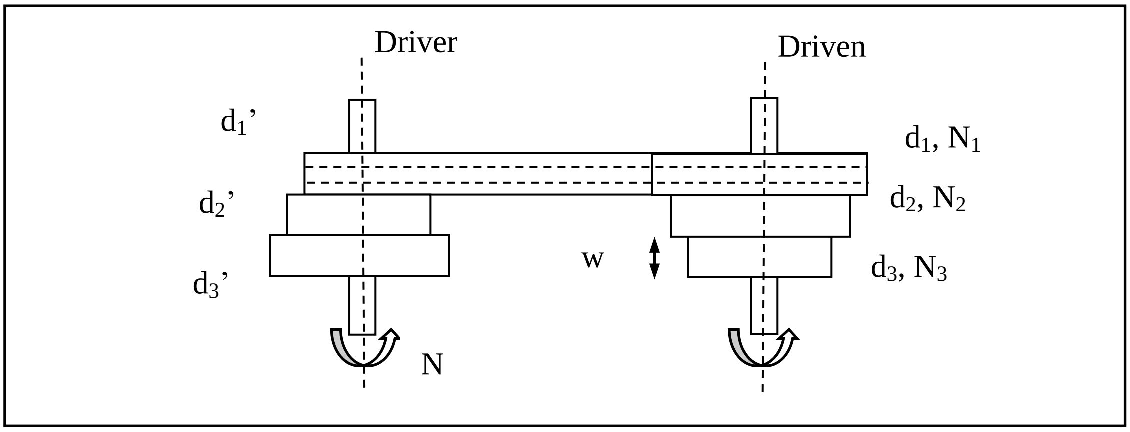


Fig. 5.2: Three step cone CVT

5.2 Optimal Problem Formulation

The design vector is taken as:

$$X = [d_1, d_2, d_3, w]^T, \tag{5.1}$$

where d_i is the diameter of the i^{th} step on the output shaft and *w* is the step width. d'_i is the diameter of the i^{th} step on the input shaft and ρ is density of step cone. The required torque range of *6.3-20.6 Nm* (experimental data) is used to obtain the maximum and minimum speed limits at discrete steps. The torque values for this calculation are taken as 20.6 *Nm* (low speed), 13.45 *Nm* (medium speed) and 6.3 *Nm* (high speed). The input speed, N (from the driving Maxon motor, P = 100 *W*) is 3,490 rpm and the three speed steps after calculations using speed-torque relations ($P = 2\pi NT/60$) are 46, 71 and 151 rpm.

The objective function $f(x)$ is taken as weight of the step cone CVT which is to be minimized:

$$f(x) = \rho w \frac{\pi}{4}\left[d_1^2 + d_2^2 + d_3^2 + {d'}_1^2 + {d'}_2^2 + {d'}_3^2\right] \quad (5.2)$$

$$= \rho w \frac{\pi}{4}\left[d_1^2\left\{1 + \left(\frac{N_1}{N}\right)^2\right\} + d_2^2\left\{1 + \left(\frac{N_2}{N}\right)^2\right\} + d_3^2\left\{1 + \left(\frac{N_3}{N}\right)^2\right\}\right]$$

$$= 2700w \frac{\pi}{4}\left[d_1^2\left\{1 + \left(\frac{46}{3490}\right)^2\right\} + d_2^2\left\{1 + \left(\frac{71}{3490}\right)^2\right\} + d_3^2\left\{1 + \left(\frac{151}{3490}\right)^2\right\}\right] \quad (5.3)$$

Belt should be equally tight on corresponding steps, the overall length of the belt must be kept invariant for all the output speeds. This can be ensured by satisfying the following equality constraints:

$$h_1(x) = L_1 - L_2 = 0, \quad (5.4)$$

$$h_2(x) = L_1 - L_3 = 0, \quad (5.5)$$

where L_i denotes belt length [8] and is given by:

$$L_i = \frac{\pi d_i}{2}\left(1 + \frac{N_i}{N}\right) + \frac{\left(\frac{N_i}{N} - 1\right)^2}{4b} + 2b \quad (5.6)$$

where b is the distance between the shafts axis, taken as 0.1 m.

The constraint for ratio of tensions which usually taken as two units, can be expressed as:

$$g_{1,2,3}(x) = R_i \geq 2, \quad (5.7)$$

where the tension ratio (R_i) is as under:

$$\frac{T_1^i}{T_2^i} = e^{\mu\theta_i}, \quad (5.8)$$

where $T_1^i$and T_2^i are the tensions on the tight and slack sides of the belt, μ is the coefficient of friction, and θ_i the angle of lap of the belt drive. The angle of lap is given by:

$$\theta_i \quad = \quad \pi - 2\sin^{-1}\left\{\left(\frac{N_i}{N} - 1\right)\frac{d_i}{2b}\right\} \tag{5.9}$$

Parameter values are presented in tabular form in Table 5.1 are given below.

Table 5.1: Parameters of a step cone CVT

Parameter Description	**Symbol**	**Units**	**Value**
Density of aluminum step cone	ρ	kg/m^3	2700
Centre distance	a	m	0.1
Coefficient of friction between aluminum cone and rubber belt	μ	NA	0.30
Maximum Stress value	s	N/m^2	1.75 x 10^6
Thickness of belt	t	m	0.005
Input motor speed (Maxon motor, 100 W) with reduction of 1:10 for input to CVT	N	rpm	349
Output Speed 1	N_1	rpm	160
Output Speed 2	N_2	rpm	290
Output Speed 3	N_3	rpm	425

The constraint for power transmitted is given as below:

$$g_{5,6,7}(x) \quad = \quad P_i \ \geq \ 100, \tag{5.10}$$

where P_i is expressed [93] as:

$$P_i \quad = \quad stw\left[1 - \exp\left[\mu\left\{\pi - 2\sin^{-1}\left\{\left(\frac{N_i}{N} - 1\right)\frac{d_i}{2b}\right\}\right\}\right]\right]\frac{\pi d_i N_i}{60}z \qquad (5.11)$$

where *s* is the maximum allowable stress (1.75 x 10^6 N/m^2) in the belt and *t* is the thickness of the belt. Finally, the variable bounds are taken as:

$$w \geq 0 \qquad (5.12)$$

$$d_i \geq 0 \quad \forall\, i = 1, 2, 3. \qquad (5.13)$$

All the values for the various constants used in the formulation of the optimization problem are taken from experimental data as described in Table 5.2 and unavailable data is assumed according to the range of the assistance needed. The optimization problem has ten constraints, which includes two equality and eight inequality constraints.

Table 5.2: Torque range data

[Experimental Data, PhaseX SWEDEN]

STS Time [sec]	Max torque requirements for **Sit-to-Stand** [Nm]								
	Hip			Knee			Ankle		
	70kg	80kg	90kg	70kg	80kg	90kg	70kg	80kg	90kg
1	91	104	117	80.3	92	103	56	65.3	72
2	57,3	65.3	73.7	70	80	90	33,3	38.3	43
4	49.7	56.8	63.9	67.2	76.8	86.4	28.7	32.8	36.9
7	45.3	52	58	66.3	76	85	25.6	29.3	33

5.3 Optimization Results

This optimal problem is solved by two different methods using MATLAB routines. The complete code is developed in MATLAB environment. The optimized values for the diameters and the width of the three step cone CVT are presented in Table 5.3. Inbuilt MATLAB function *fmincon* is used for optimization of this non-linear function. These values can be further used for experimental prototyping and validation for use in exoskeletons for healthy elderly.

Table 5.3: Optimal values of the CVT design variables (mm)

Variable	d_1	d_2	d_3	w
MATLAB function (*fmincon*)	102	70	36	6

These dimensions are further used for geometrical modeling and analysis of the CVT by coupling it with mechanisms explained in next chapter.

5.4 Summary

In this chapter, a three step cone CVT has been considered and an optimization problem is formulated to minimize the weight of the CVT. For this, the objective function is optimized in the MATLAB environment and the results are obtained. The obtained results fall in the feasible practical range that will be further used in designing the CAD model of the CVT based hybrid mechanism.

Chapter 6

Modeling and Simulation of a Hybrid Mechanism

6.1 Introduction

As discussed in Chapter 3, the limitations of conventional methods used for torque variation and motion reversal lead to the investigation of a new technique to eradicate all those limitations and to make torque variation more effective, user controlled and low-cost. The concept of hybrid mechanisms is coined to focus on the cost minimization of the exoskeleton. In this chapter, the concept of a hybrid mechanism is presented for torque variation and motion reversal of the knee exoskeleton. Over the last two decades, various devices under the category of wearable robots have been developed which includes HAL [55], LOPES [18], ekso [13], ReWalk [11], etc. as discussed in Table 2.1. Most of them use electric actuators like DC motors to give motion to the wearers' joints e.g. in HAL [55] etc. These motors are coupled with inbuilt microcontrollers or external control systems to alter the rpm/torque of the motor. This requires instantaneous change in the power supplied to the motor and reversal of motor polarity and leads to increase in torque requirement.

This problem is found in all those exoskeletons which use gearhead and harmonic drives with the motor. Harmonic drives are used for large reduction ratio to provide required torque; these devices are very efficient in nature but are extremely costly. Moreover, by using gearheads and harmonic drives, the overall efficiency of the drive is reduced and the metabolic cost also increases. To eradicate these problems of motion reversal, optimal torque requirement and preventing power losses, a viable solution is needed which can provide required torque at required joint without altering the power input and polarity of the motor. This can only be done by coupling the motor with an external mechanism/device which does all this without disturbing the constant rpm of the motor. The concept of CVT brought forward in Chapter 5 is used for torque variation purpose and its feasibility with the conventional mechanisms is checked. Further, conventional mechanisms are investigated for their feasibility in wearable exoskeleton for healthy elderly. This is done by analytical modeling of the mechanisms and then geometrical modeling for visualization and validation of the analytical model. Further, the results are compared with the normal gait cycle of an average human being, which is explained briefly in next section.

6.2 Normal Gait Cycle

Normal gait cycle is the sequence of the complete movement of the human leg from the point where the toe leaves the ground and when it completes one step and again touches the ground. It is also called bipedal gait or stride [92]. Mainly gait is divided into two parts: *stance* and *swing* phase as shown in Fig. 6.1 in which the desired angle vs. gait cycle is also depicted for ankle, knee and hip joint. This desired angle variation is useful during the validation stage of the hybrid mechanism. The current thesis is limited to knee joint study only.

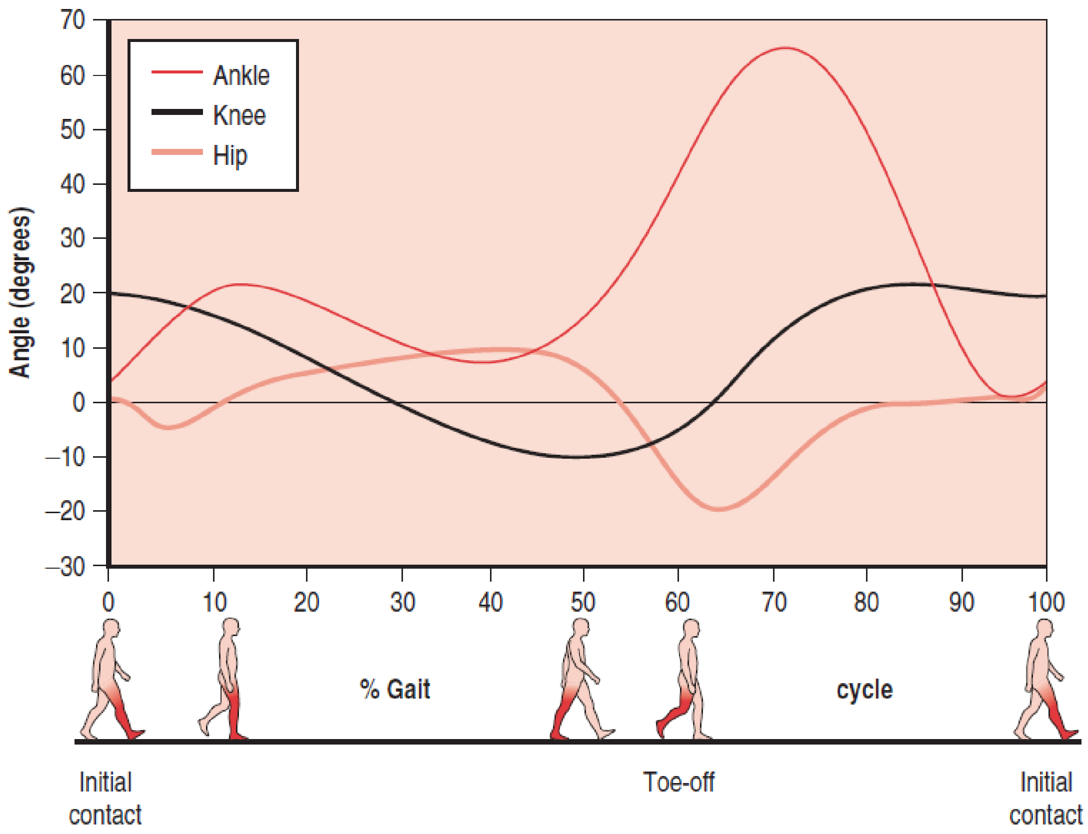


Fig. 6.1 Gait cycle of average human being [92]

6.2.1 Stance Phase

Stance phase is the time interval during which the foot is touching the ground, but for some period of stance both feet will be touching the ground. It is called the weight bearing phase of the gait cycle. Stance Phase is divided into:

1) Heel strike to foot flat

2) Foot flat through mid-stance

3) Mid-stance through heel off

4) Heel off to toe off

6.2.2 Swing Phase

Swing phase is the time interval of the gait cycle in which the foot is not in contact with the ground. It is basically the period in which foot is midway in the air. It is the period when foot is in forward motion. It is divided into two phases i.e. *Acceleration to mid-swing* and *Mid-swing to deceleration*.

6.3 Hybrid Mechanism

As the CVT concept is discussed in last chapter, this section explains how mechanisms can be fitted into the exoskeleton for providing required torque and direction at the required time interval. For this, scotch yoke mechanism is used to convert the rotary motion from the motor (or from CVT, after torque enhancement) to linear motion and the then the linear motion is restricted according to the angular arc of knee joint as per human gait cycle, by using a four-bar mechanism. Both mechanisms and their possible use in the exoskeleton for elderly are explained below.

6.3.1 Scotch Yoke Mechanism

Scotch yoke mechanisms convert continuous rotary motion into reciprocating linear motion and have been used in internal combustion and steam engines.

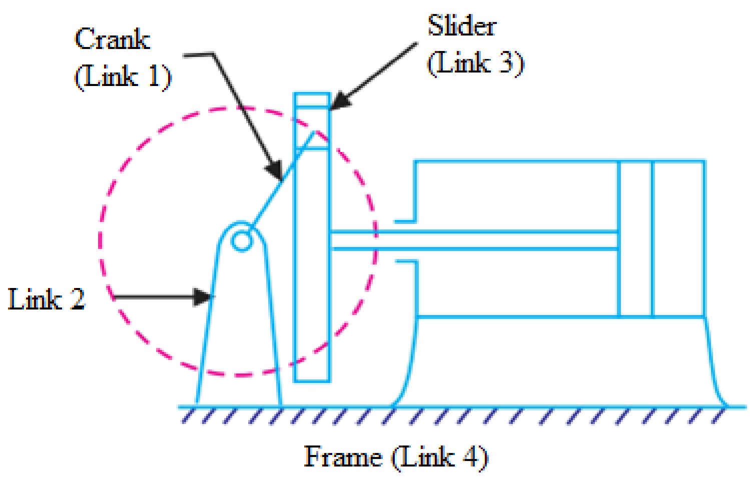


Fig. 6.2: Scotch yoke mechanism

These mechanisms are similar to a crank and slider mechanism in that the linear output moves in a sinusoidal pattern except Scotch yoke mechanisms have fewer moving parts and are capable of higher torque output because of which it have been taken into consideration in this work. Figure 6.2 shows this mechanism and it starts with the slider all the way to the right. As the crank rotates counter clockwise, the roller attached to the crank pushes the slider to the left. After the crank has rotated 180 degrees the slider reaches the end of its range of motion and as the crank continues to rotate the slider begins to move toward the right. This reciprocating motion continues as long as the crank continues to turn. When the crank rotates at a constant velocity the slider reaches its maximum velocities when the crank is at initial position and final position. At the knee joint of the exoskeleton, this principle can be utilized as the complete rotary motion of the motor is not required at knee, only a partial motion is required. For that first of all, the reciprocating motion of the motor/CVT is converted to linear motion for feeding the output to next mechanism i.e. four bar mechanism.

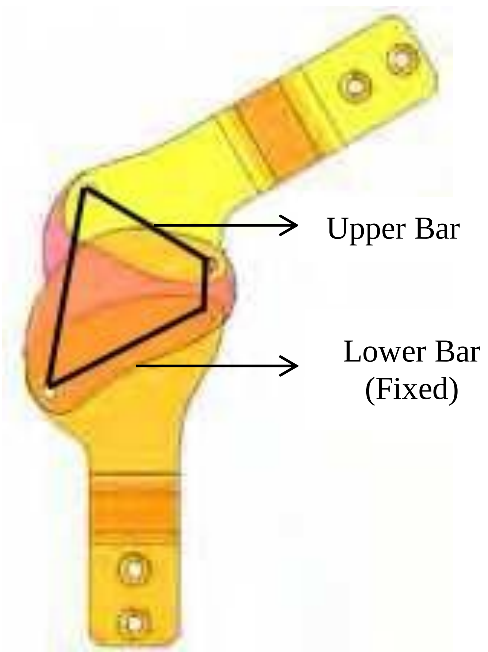


Fig. 6.3: Four-bar mechanism for sit-to-stand posture [90]

6.3.2 Four-bar mechanism

A four-bar mechanism [88] is usually chosen to transfer motion form a link to another with some variation in torque or moment. A four-bar mechanism was chosen for the exoskeleton knee joint because it allows movement in normal range and has a polycentric nature [89]. It also helps in avoiding any link migration and unwanted forces. Restrictions are applied mechanically to constrain the knee movement within normal range of the knee, between 0 to 135 degrees. During sit to stand motion, the lower bar is fixed and all other three bars are in motion whereas while walking and running the order is reversed i.e. the lower bar is in movement, while upper bar which supports the thigh portion is in state of rest. The model of the four-bar mechanism used in the analysis is shown in Fig. 6.3 and is inspired from the design of Pons et al. [90].

6.4 Mathematical Model of the Hybrid Mechanism

For mathematical modeling of the complete mechanism, individual transfer functions of all three mechanisms are derived and concatenated. The flowchart of the complete system and the corresponding diagrams is shown in Fig. 6.4.

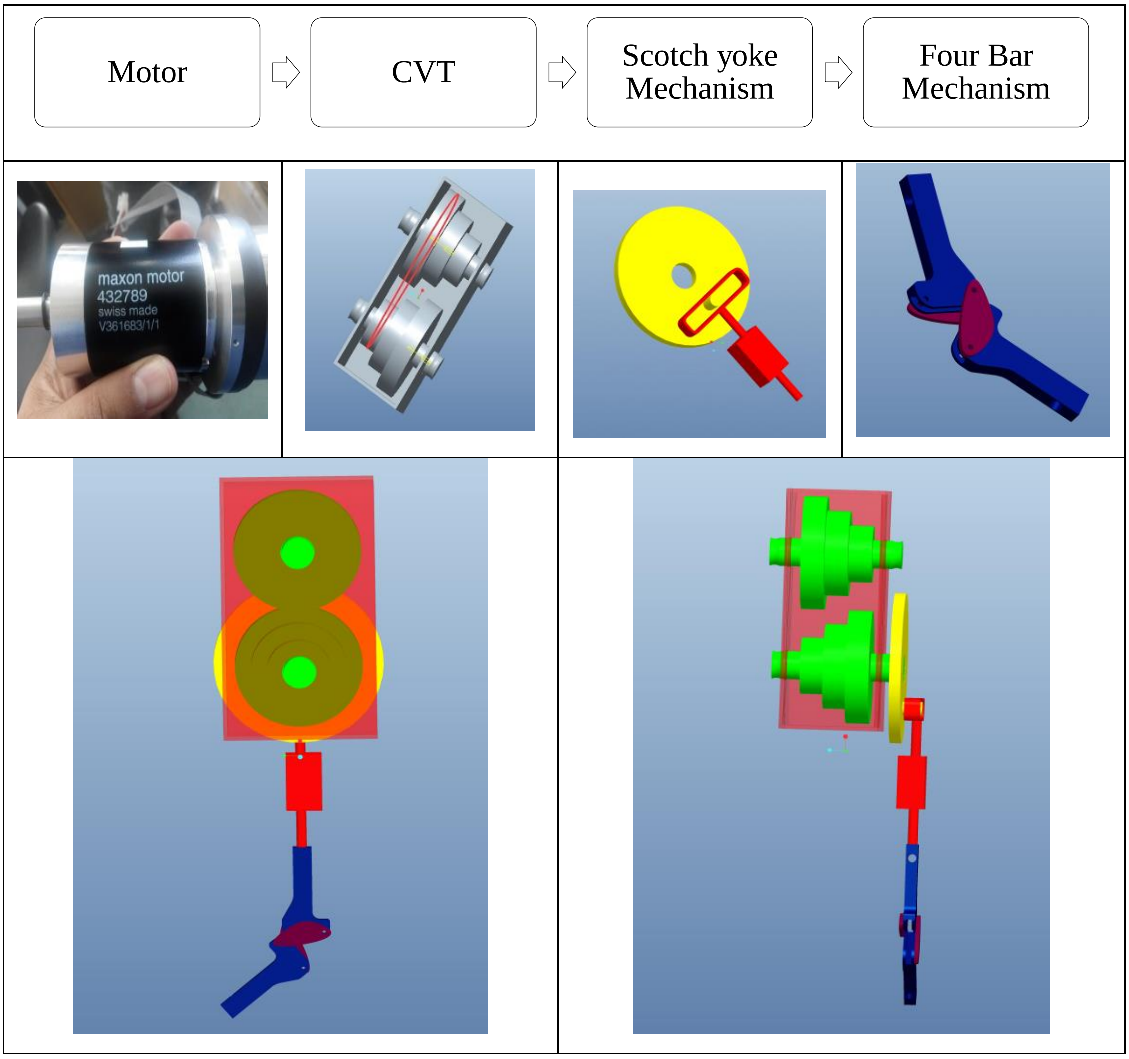


Fig. 6.4: System flowchart and assembly views

As discussed in Section 5.1, the input torque (τ) from the Maxon motor for the knee joint is 0.319 Nm, which is increased by 10 times using a speed reduction belt drive coupled with motor, to feed the CVT with 3.19 Nm torque. The final output torque obtained at output shaft of the CVT (τ_{sci}) is given by relation between torque and diameter ratio, which is derived from the mathematical derivation of the CVT in Chapter 5.

$$\frac{\tau}{\tau_{sci}} = \frac{d_i'}{d_i} \tag{6.1}$$

The torque exerted on the crank of the scotch yoke mechanism by the motor is amplified by the geometry of the scotch yoke mechanism as well as the current angle of rotation of the wheel. The relation between input and output torque of a scotch yoke is given below and is derived from work of Clausen [87].

$$\tau_{fbi} = \frac{c}{psin(\theta_w)} \eta \times \tau_{sci} \tag{6.2}$$

where τ_{sci} is the torque applied to the scotch yoke from the CVT, τ_{fbi} is the input torque required at the four-bar mechanism, which is determined from biomechanics data, θ_w is the current crank angle, η is the efficiency (assumed to be 0.98, neglecting friction), p is the distance between the centre of the crank and centre of the roller, c is the distance between the centre of the crank and the point where the steel cable connects to the leg bar. Using kinetic energy equation, one obtains the equation of motion of mechanism as follows. The complete solution in terms of input and loading moments is explained by Yildiz et al. [91], in which four-bar mechanism is controlled by a CVT and is given as

$$M_{l,r} = M_{in} - N\ddot{\emptyset}_2 - \frac{1}{2}\frac{dN}{d\emptyset_2}\dot{\emptyset}_2 \tag{6.3}$$

After combining (6.1), (6.2), (6.3) and solving by using superposition principle, (6.3) can be written as

$$M_{l,r} = \left(\frac{d_i \tau}{d_i{}'} \times \frac{c}{psin(\theta_w)} \eta\right) - N\ddot{\emptyset}_2 - \frac{1}{2}\frac{dN}{d\emptyset_2}\dot{\emptyset}_2 \tag{6.4}$$

where M_{in} is the input moment to the four-bar mechanism which is equal to τ_{fbi}, $M_{l,r}$ is the equivalent loading moment. $N\emptyset_2$ is the equivalent mass moment of inertia. Now, this complete mathematical equation was plotted for angle and torque output vs. gait cycle (time) in MATLAB environment. The plots are shown in Fig. 6.5 and Fig. 6.6 respectively.

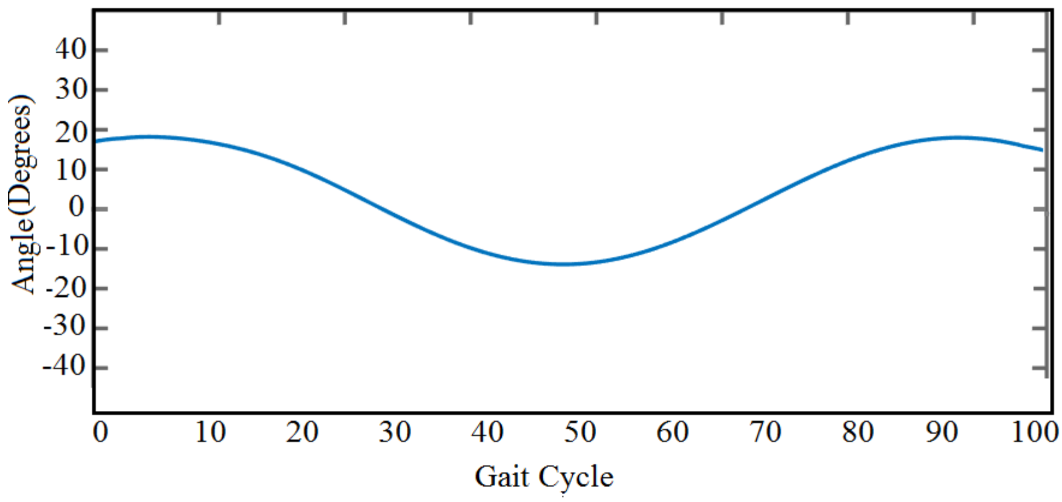


Fig. 6.4: Position vs. gait cycle (Analytical)

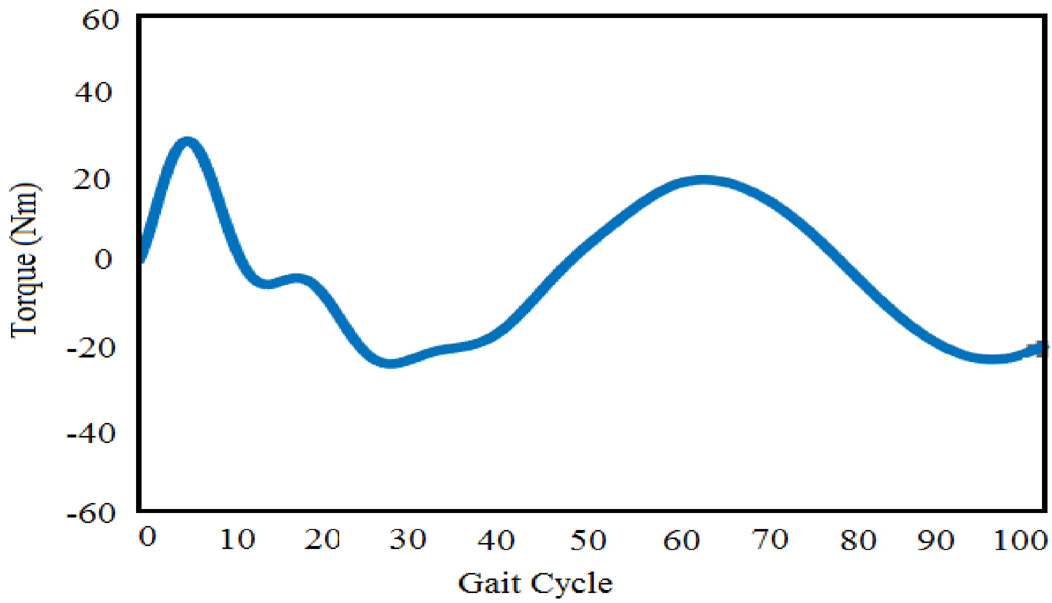


Fig.6.5: Torque Vs. Gait cycle (Analytical)

The plot in Fig. 6.5 shows the change in angular position of the knee joint as the normal human being is executing the walking gait cycle. The plot crosses two times the base line of zero, once in stance phase and other in swing phase which is as expected. So far up to this step our design seems feasible as all criteria are met as desired. In the plot shown Fig. 6.6, it is seen that initially there is an overshoot peak because the stance phase in almost no time and finally the torque stays between the required range after which as joint starts moving into swing phase. In next section the similar plots are obtained from simulation of the geometrical model of the proposed mechanism.

6.5 Geometrical Model of the Hybrid Mechanism

In order to check the authenticity of the mathematical model, the geometric model of the complete assembly was made, as shown in Fig. 6.7 and then imported to MATLAB environment for simulation to obtain plots of position and torque exerted. SolidWorks 2013 version was used to model the parts and complete assembly.

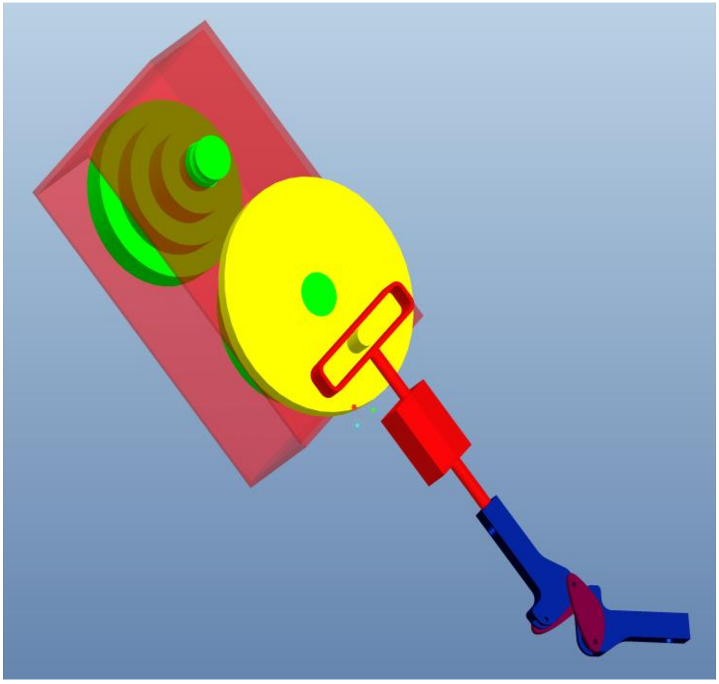


Fig. 6.7: Geometric model of the complete assembly

First of all, the knee joint was modeled according to specifications of a human knee. These joints are assembled and contact restriction between them is applied. After this CVT is modeled and assembled with proper constraints, can rotate with desired speed ratio according to the mathematical formulation. The next step is modeling of the scotch yoke mechanism so that linear motion of knee joint could be achieved by conversion of rotating motion from CVT. Finally, all these sub-assemblies are assembled and simulation is performed.

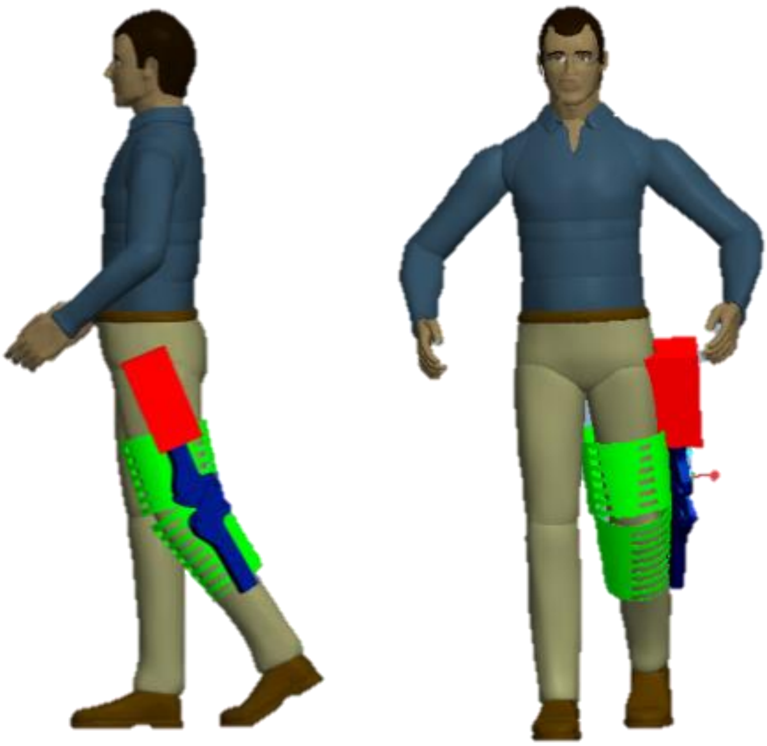


Fig.6.8: Assembly installed on human body, showing knee joint with mechanism

Belt drive is used to connect two steps of CVT and speed ratio is kept to be 0.5 for initial calculations. The output shaft of CVT was attached to a scotch yoke mechanism, finally the shaft of which was attached to the designed four-bar knee joint. As this study is restricted to walking gait cycle, the upper bar is considered as the fixed link, thus the movement of other three bars execute the four-bar mechanism and resembles the walking pattern similar to walking gait cycle. After this complete assembled model was installed on Manikin (virtual human model) as shown in Fig. 6.8, to see the feasibility of design and also to obtain the simulation videos to obtain the integration of our design with human walking. The weight of the complete assembly as checked in SolidWorks is only *16 kgs*, which is a workable value if compared with other exoskeletons of similar design. For simulation, the final CAD model is exported from SolidWorks i.e., its design workplace to Simulink software. For this purpose the .xml file was created which is later imported by Simulink software with use of proper keywords. Thereafter .slx file was created, which is an extension of Simulink file, where complete block diagram structure of assembly is obtained.

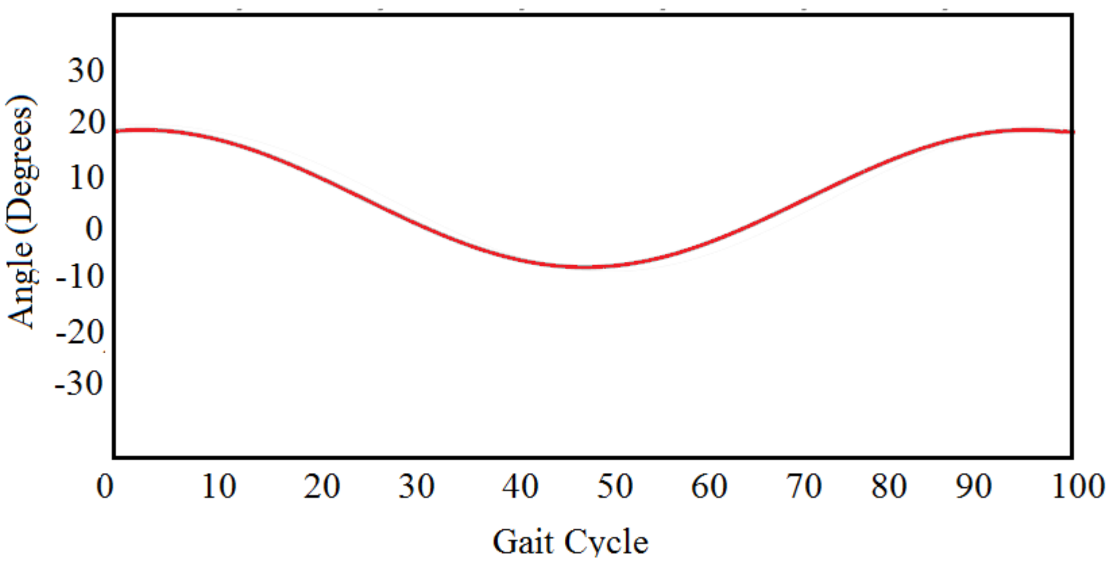


Fig. 6.9: Position vs. gait cycle (Simulation)

For simulation purpose, saturation block treatment is applied in order to limit upper and lower values of amplitude resulting from scotch yoke mechanism. Normal range of motion at the knee is considered to be 0 degrees of extension (completely straight knee joint) to 135 degrees of flexion (fully bent knee joint). Walking requires complete knee extension as the heel strike and up to 60 degrees of flexion range with maximum peak value of 20^o. One complete gait cycle consists of two phases i.e. stance and swing phase. Now the plots of the angle and torque were obtained from Simulink Environment and are shown in Fig 6.9 and 6.10 respectively. The initial angle according to literature is 20^o when the toe comes in contact with the ground and then finally completing both the phases. The results obtained from Simulink interface are shown in Fig. 6.9, where it can be clearly seen that the range of motion comes out to be 60^o [-30^o to 30^o] and maximum peak angle is 20^o. At the beginning of gait cycle, joint angle comes out to be 20^o and decreases to zero, this is called the *stance phase,* which is much smaller as compared to the *swing phase,* in which extension takes place and at end, the joint reaches once again at its initial position. From the simulation, it can be inferred that whole cycle goes with much smoother variation thus giving the better control over the designed knee joint of the exoskeleton structure. Fig.

6.10 gives a depiction of torque vs. gait cycle plotted from simulation of the assembly of the complete mechanism.

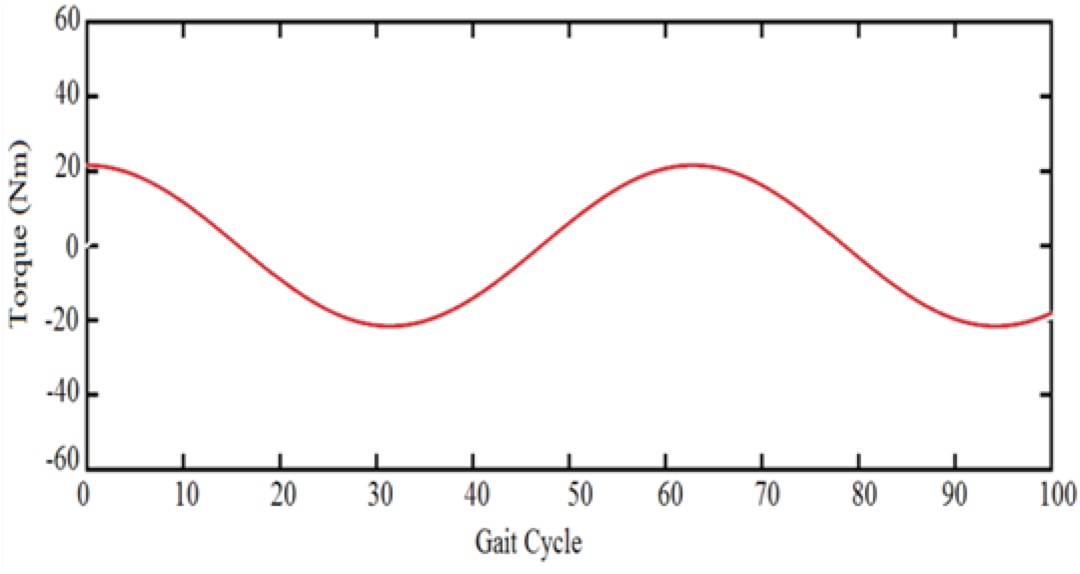


Fig. 6.10: Torque vs. gait cycle (Simulation)

6.6 Simulation Results and Validation

In this section, validation is carried out where both the results obtained from mathematical modelling and geometrical modeling are compared with the normal biomechanical walking data. This is done by superimposing the graphs obtained by simulation and MATLAB with normal gait cycle of a human being. Fig. 6.11 and 6.12 shows the comparison between the results obtained from the mathematical transfer function approach, geometrical modelling approach via Simulink and the reference trajectory of normal human walking [92]. In first case as depicted by Figure 6.11 above, the plots of knee angular position are compared, which shows that the model is able to control the limits of motion very well in range of 60^{o}. Initial and final angle is also the same, which concludes that design of hybrid mechanism proposed in this thesis works as effectively as using costly controllers. The only difference observed was slight change in duration of stance phase and how the slope of graph varies. Further improvement could be done in future work by trying better strategies and improvement in design. In second case, in order to verify the torque variations, the results are compared with the normal human walking torque data as shown in Fig. 6.12 [92].

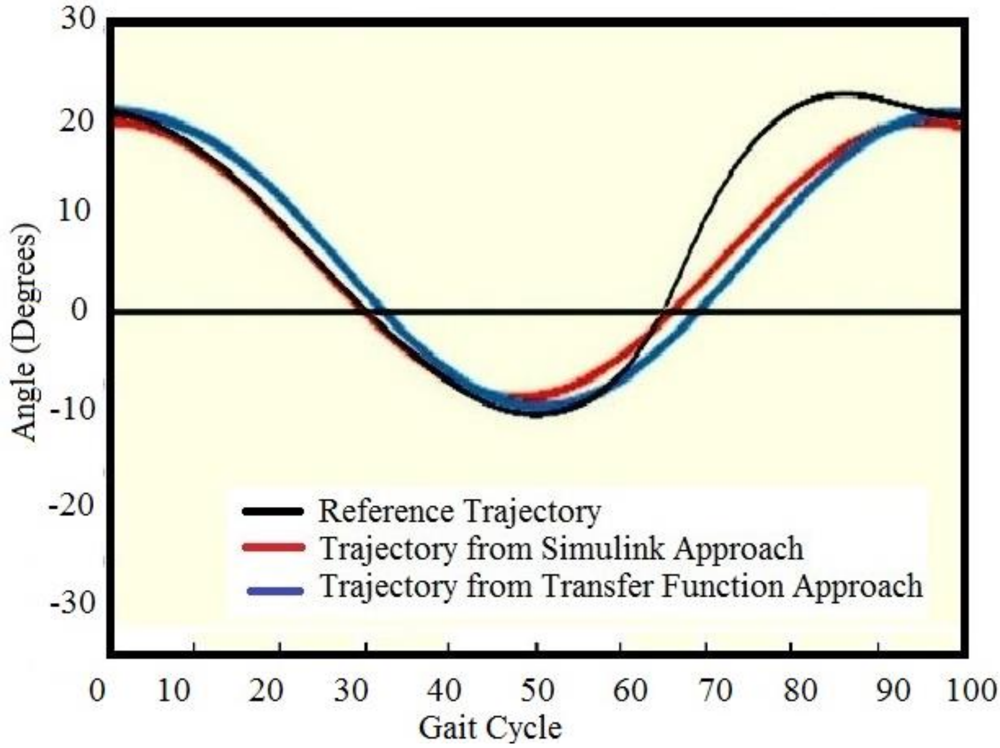


Fig. 6.11: Position vs. gait cycle validation

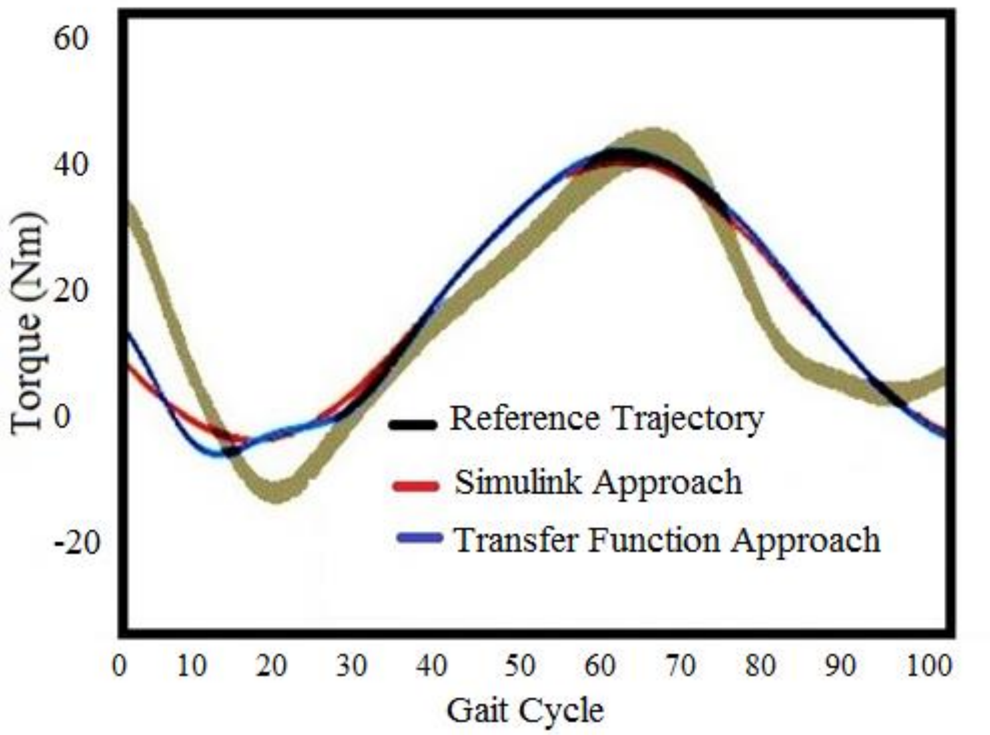


Fig. 6.12: Torque vs. gait cycle validation

6.7 Summary

From Swedish experimental data, it is found that for a knee exoskeleton, the torque range is 20-26 Nm during walking gait cycle. For this torque range, the simulation results have been obtained using the hybrid mechanism and are found in close agreement except the initial overshoot, which is nearly 30 Nm. This work shows only one speed ratio of CVT at initial level which has been verified for different ratios also. In order to understand the effect of the CVT ratio on the variation of the angular speed of crank, the simulation has been repeated over physically possible range of ratios of CVT. To sum up, the simulation results show that using a CVT for obtaining variable input speed in conjunction with scotch yoke mechanism and a four-bar linkage is feasible under all circumstances.

Chapter 7

Conclusions and Future Directions

7.1 Conclusions

The study on lower-limb exoskeletons is carried out which focuses mainly on the design part of the torque variation and motion reversal methods. The major findings are concluded below:

- This thesis classifies current exoskeletons which have emerged and gives insight into their mechanical and electrical components including key issues such as actuators, control strategy, sensors, powering methods, mechanisms and materials. A comprehensive literature survey was done for this, highlighting the less explored research areas and suggesting suitable trending applications where exoskeletons should be employed.
- The other aim of the classification and comparison of wearable exoskeletons was to bring out issues where improvements are needed in the existing exoskeleton and to allow the research and development focus to be made in relevant technology areas for advancing lower-limb exoskeletons.
- The need for safety standardization and regulation in medical and non-medical wearable devices was introduced and its impact on the overall process to deliver the urgently needed products to the market place in medical and non-medical applications. As a whole, it is hoped that this thesis work will help researchers and academicians to have a comprehensive state-of-the-art presentation on the lower-limb exoskeletons and will enable the community to review and realign research efforts to maximize impact in the rapidly evolving area of personal care robots by keeping in mind the issues of safety and standardization.
- The feasibility of a step cone CVT for use in lower limb exoskeleton is done which can significantly reduce the cost of the exoskeleton as the methods used till now for torque variation in exoskeletons add to its overall cost and also result in overdesigning of the exoskeleton.
- The optimization formulation of step cone CVT has been performed in this work in order to minimize the CVT weight. Results were obtained using optimization

techniques in MATLAB environment. Moreover, this type of solution is more suitable to healthy elderly, as they need only 10-20% assistance and can manually change the lever to get the required speed ratio, instead of depending on high-cost microcontrollers.

- Adding to the research, a hybrid mechanism has been proposed using traditional mechanisms viz. scotch yoke and four bar mechanism were investigated for feasibility in lower-limb exoskeletons. This was done by modeling it with conjunction with CVT in Pro-E and then simulation in Simulink.
- Finally, the results from geometric model of the complete mechanism assembly were compared with mathematical analysis and validated with the normal walking gait cycle.

7.2 Future Directions

Future directions of lower-limb exoskeletons will depend on consumer responses to how the needed mass markets which depends on factors like affordability, effectiveness, comfort, and safety certification. Some key issues in this regard are summarized to highlight the urgently needed future directions in developing the area of lower-limb exoskeletons –

- Future actuators for exoskeletons must be light weight, low cost, noise free, compact and high precision may be questioned. Also they should be able to provide high needed torques at the required speeds without use of expensive harmonic drives. Series elastic actuators could be developed keeping in mind the torque, speed and weight requirements. Another option could be using specially developed mechanisms with integrated light weight motors to achieve required torques/speeds at the joints.
- The overall comfort and better fit of the exoskeletons needs to be worked on; this will not only allow for long duration wearability but will also add a sense of satisfaction and independence.
- General purpose or multipurpose devices should be avoided. However, special variants can be made for specific application areas. For example, in the EXO-LEGS project, a modular approach has been adopted where three mobility exoskeletons have been focused upon, namely Basic, Standard and Deluxe versions. These variants are designed to support different mobility functionalities

with the basic providing the most important and essential mobility functions such as stable standing, sit-to stand transfers and straight walking in the sagittal plane. The Standard exoskeleton extends the functionalities by also including more advanced motion support such as walking and turning, bending to pick an item from the floor, stepping over objects, going up/down stairs, and walking on ramps. The Deluxe design adds further motion functions such as speed walking, walking on uneven ground and exercising, etc. Such flexible design approaches will not only add to the customization of the exoskeleton but will also make it more cost effective.

- Actuators, batteries and other components should be designed in such a way to minimize maintenance.
- New powering technologies apart from conventional batteries should be looked into which are not only autonomous but also more cost effective and environmental friendly. This can be realized by taking power from human efforts and using alternative power sources.
- More focus is required on studying the details of the various motions human have to perform and make the use of exoskeletons more comfortable and trouble free for the wearers.
- Only a few exoskeletons have been realized which are able to provide full stabilization, without supporting crutches/sticks. This increases the weight of the exoskeleton significantly. This aspect needs to be worked on, to make the exoskeletons lightweight without compromising the stability.
- Better mechanisms for torque variation and motion reversal at joints to enable quick motion without fuss are needed.
- Level of assistance for lower-limb exoskeleton for elderly should be configurable, so that the wearer can decide the level of assistance needed from the worn exoskeleton.

REFERENCES

[1] M. Vukobratovic, “Legged locomotion robots and anthropomorphic mechanisms”, Mihailo Pupin Institute, Belgrade, 1975

[2] UN Population division, “World population ageing 2015”, Population face sheet URL: http://www.un.org/en/development/desa/population/publication/pdf/popfacts/PopFacts_2014-4Rev1.pdf, October 2015, Accessed on: 16 Jan 2016

[3] A. J. Young, D. P. Ferris, “State-of-the-art and future directions for lower limb robotic exoskeletons”, IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2016

[4] H. Herr, “Exoskeletons and orthoses: classification, design challenges and future directions”, Journal of Neuro Engineering and Rehabilitation, Vol. 6, No. 1, 2009

[5] S. Viteckova, P. Kutilek, M. Jirina, “Wearable lower limb robotics: A review”, Biocybernetics and biomedical engineering, Vol. 33, pp. 96–105, 2013

[6] W. Huo, S. Mohammed, J. C. Moreno, and Y. Amirat, “Lower limb wearable robots for assistance and rehabilitation: A State of the Art”, IEEE Systems Journal, pp. 1–14, 2014

[7] B. S. Rupal, A. Singla, G. S. Virk, “Lower limb exoskeletons: A brief review”, Conference on Mechanical Engineering and Technology (COMET-2016), IIT (BHU), Varanasi, India, pp. 130–140, 2016

[8] B. Chen, H. Ma, L.Y. Qin, F. Gao, K. M. Chan, S. W. Law, L. Qin, W. H. Liao, “Recent developments and challenges of lower extremity exoskeletons”, Journal of Orthopaedic Translation, Vol. 5, pp. 26-37, 2016

[9] R.A.R.C. Gopuraa, D.S.V. Bandara, K. Kiguchi, G.K.I. Mann, “Developments in hardware systems of active upper-limb exoskeleton robots: A review”, Robotics and Autonomous Systems, Vol. 75, pp. 203–220, 2016

[10] R. J. Farris, H. A. Quintero, S. A. Murray, K. H. Ha, C. Hartigan, M. Goldfarb, “A preliminary assessment of legged mobility provided by a lower limb exoskeleton for persons with paraplegia”, IEEE Transactions on neural systems and rehabilitation engineering, Vol. 22, No. 3, pp. 482–490, 2014

[11] G. Zeilig, H. Weingarden, M. Zwecker, I. Dudkiewicz, A. Bloch, A. Esquenazi, "Safety and tolerance of the ReWalk™ exoskeleton suit for ambulation by people with complete spinal cord injury: A pilot study", The Journal of Spinal Cord Medicine, Vol. 35, No. 2, pp. 101–96, 2012

[12] R. J. Farris, H. A. Quintero, and M. Goldfarb, "Preliminary evaluation of a powered lower limb orthosis to aid walking in paraplegic individuals," IEEE Transactions on Neural Systems and Rehabilitation Engineering, Vol. 19, No. 6, pp. 652-659, 2011

[13] S. A. Kolakowsky-Hayner, J. Crew, S. Moran, A. Shah, "Safety and feasibility of using the EksoTM bionic exoskeleton to aid ambulation after spinal cord injury", Journal of Spine, 2013

[14] A. Kilicarslan, S. Prasad, R. G. Grossman, and J. L. Contreras- Vidal, "High accuracy decoding of user intentions using EEG to control a lower-body exoskeleton", International Conference of the IEEE Engineering in Medicine and Biology Society, pp. 5606–5609, 2013

[15] URL: http://www.wandercraft.eu/lexosquelette.html, Accessed on: 26 Feb. 2016

[16] J. Gancet, M. Ilzkovitz, E. Motard, Y. Nevatia, P. Letier, D. de Weerdt, et al., "MINDWALKER: Going one step further with assistive lower limbs exoskeleton for SCI condition subjects", RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics, pp. 1794–1800, 2012

[17] I. Dıaz, J. J. Gil, E. Sanchez, "Lower-Limb Robotic Rehabilitation: Literature Review and Challenges", Journal of Robotics, 2011

[18] G. Chen, C. K. Chan, Z. Guo, H. Yu, "A Review on Lower Extremity Assistive Robotic Exoskeleton in Rehabilitation Therapy", Critical Reviews in Biomedical Engineering, Vol. 41, No. 4-5, 2013

[19] G. Colombo, M. Joerg, R. Schreier, and V. Dietz, "Treadmill training of paraplegic patients using a robotic orthosis", Journal of Rehabilitation Research and Development, Vol. 37, No. 6, pp. 693–700, 2000

[20] S. Freivogel, J. Mehrholz, T. Husak-Sotomayor, and D. Schmalohr, "Gait training with the newly developed "LokoHelp"-system is feasible for non-ambulatory patients after stroke, spinal cord and brain injury. A feasibility study", Brain Injury, Vol. 22, No. 7-8, pp. 625–632, 2008

[21] Rafael R. Torrealba, G. Ferna´ndez-Lo´pez and Juan C. Grieco, "Towards the development of knee prostheses: review of current researches", Kybernetes, Vol. 37, No. 9-10, pp. 1561–1576 , 2008

[22] Dietl, H., Kaitan, R., Pawlik, R. and Ferrara, P. (1998), "C-Leg ein neues System zur Versorgung von Oberschenkel-amputationen" ("C-Leg – a new system for

prosthetic management of A/K amputations"), Orthopa¨ die Technik, Vol. 49, pp. 197–211, 1998

[23] URL: www.ossur.com/template110.asp?pageid ¼ 24, Accessed on: 4 Jan. 2016

[24] URL: http://professionals.ottobockexport.com/cps/rde/xchg/ottobock_export_en/hs.xsl/229.html , Accessed on : 17 March 2016

[25] K. Yamamoto, M. Ishii, K. Hyodo, T. Yoshimitsu, and T. Matsuo, "Development of power assisting suit (miniaturization of supply system to realize wearable suit)", JSME International Journal Series C, Vol. 46, No. 3, pp. 923–930, 2003

[26] URL: www.suitx.com/phoenix, Accessed on: 8 Jan. 2016

[27] H. Kazerooni and R. Steger, "The Berkeley Lower Extremity Exoskeleton", ASME Journal of Dynamic Systems, Measurement, and Control, Vol. 128, No. 1, pp. 14–25, 2006

[28] E. Guizzo, H. Goldstein, "The rise of the body bots", IEEE Spectrum, Vol. 42, No. 10, pp. 50–56, Oct. 2005

[29] URL: http://www.army-technology.com/projects/human-universal-load-carrier-hulc/, Accessed on: 10 Jan. 2016

[30] URL: http://bleex.me.berkeley.edu/research/exoskeleton/exoclimber/, Accessed on: 16 Jan. 2016

[31] URL: http://biology-forums.com/index.php?action=gallery;sa=view;id=9333, Accessed on: 10 Jan. 2016

[32] URL: http://www.gizmag.com/lockheed-martin-lab-testing-hulc-exoskeleton/16768/, Accessed on: 10 Feb. 2016

[33] URL: http://www.dailytech.com/From+HULC+to+FORTIS+the+Evolution+of+Lockheed+Martins+Incredible+Exosuit/article36421c.htm, Accessed on: 22 Feb. 2016

[34] URL: http://www.lockheedmartin.com/us/products/exoskeleton/hulc.html, Accessed on: 11 Feb. 2016

[35] URL: http://www.smh.com.au/technology/technology-news/iron-man-suit-turns-shipyard-workers-into-super-men-20140805-100n0l.html, Accessed on: 11 March 2016

[36] URL: https://www.audi-mediacenter.com/en/production-232, Accessed on: 24 March 2016

[37] URL: http://www.htxt.co.za/2015/06/23/robo-mate-exoskeleton-will-make-

factory-workers-stronger/, Accessed on: 14 March 2016

[38] URL: http://www.aal-europe.eu/, Accessed on: 12 Feb. 2016

[39] G.S. Virk, U. Haider, I. N. Indrawibawa, R. K. Thekkeparampumadom, and N. Masud, "EXO-LEGS for elderly persons", 17th International Conference on Climbing and Walking Robots (CLAWAR), Poznan, Poland, pp. 85–92, 2014

[40] URL: http://www.iso.org/iso/catalogue_detail?csnumber=53820, Accessed on: 11 Feb. 2016

[41] URL: http://bleex.me.berkeley.edu/research/exoskeleton/exohiker/, Accessed on: 16 Jan. 2016

[42] L. Gui, Z. Yang, Xiuxia Yang, W. Gu, Y. Zhang, "Design and control technique research of exoskeleton suit", International Conference on Automation and Logistics, pp. 541–546, 2007

[43] C. J. Walsh, K. Endo, H. Herr, "Quasi-passive leg exoskeleton for load-carrying augmentation", International Journal of Humanoid Robotics, Vol. 4, No. 3, pp. 487–506, 2013

[44] K.S. Stadler, W.J. Elpass, H. W. Vav De Venn, "ROBO–MATE: Exoskeleton to enhance industrial production", Mobile Service Robotics: CLAWAR, 2014

[45] J.E. Pratt, B.T. Krupp, C.J. Morse, S.H. Collins. "The RoboKnee: an exoskeleton for enhancing strength and endurance during walking", International Conference on Robotics and Automation, Vol. 3, pp. 2430–2435, 2004

[46] R. G. Baldovino, R. S. Jamisola Jr., "A survey in the different designs and control systems of powered-exoskeleton for lower extremities", 2011

[47] M. Fontana, R. Vertechy, S. Marcheschi, F. Salsedo and M. Bergamasco, "The Body Extender: A Full-Body Exoskeleton for the Transport and Handling of Heavy Loads", IEEE Robotics & Automation Magazine, Vol. 21, No. 4, pp. 34–44, 2012

[48] URL: http://www.rb3d.com/en/exo/, Accessed on: 15 April 2016

[49] URL: http://www.lockheedmartin.co.in/us/products/exoskeleton/FORTIS.html, Accessed on: 16 April 2016

[50] URL: http://activelink.co.jp/doc/668.html, Accessed on 18 April 2016

[51] N. Yagn, "Apparatus for facilitating walking", U.S. Patent No. 420179, 1890

[52] R. Rea, C. Beck, R. Rovekamp, M. Diftler, P. Neuhaus, "X1: a robotic exoskeleton for in-space countermeasures and dynamometry", AIAA SPACE Conference and

Exposition, 2013

[53] A. Seireg and J. G. Grundmann, “Design of a multitask exoskeletal walking device for paraplegics”, Biomechanics of Medical Devices, pp. 569–644, 1981

[54] M. Vukobratovic, B. Borovac, D. Surla, D. Stokic, “Scientific Fundamentals of Robotics 7, Biped Locomotion: Dynamics Stability, Control, and Application”, New York: Springer-Verlag, Vol. 8, No. 4, pp. 325–325, 1990

[55] H. Kawamoto, S. Lee, S. Kanbe, Y. Sankai, "Power assist method for HAL-3 using EMG-based feedback controller", IEEE International Conference on Systems, Man and Cybernetics, pp. 1648–1653, 2003

[56] Y. Kusuda, "In quest of mobility–Honda to develop walking assist devices" , Industrial Robot: An International Journal, Vol. 36, No. 6, pp. 537–539, 2009

[57] T. Nakamura, K. Kosuge, "Model-based walking support system with wearable walking helper", IEEE International Workshop on Robot and Human Interactive Communication, (ROMAN 2003), pp. 61–66, 2003

[58] Y. Saito, K. Kikuchi, H. Negoto, T. Oshima, T. Haneyoshi, “Development of externally powered lower limb orthosis with bilateralservo actuator”, International Conference on Rehabilitation Robotics (ICORR), pp. 394–399, 2005

[59] J. Nikitczuk, B. Weinberg, C. Mavroidis, "Rehabilitative Knee Orthosis Driven by Electro-Rheological Fluid Based Actuators" IEEE International Conference on Robotics And Automation, pp. 2283–2289, 2005

[60] URL: http://www.technaid.com/en/products/exoskeleton, Accessed on: 27 April 2016

[61] L. O’Sullivan, "Assistive exoskeletons help older adults live independent lives", Engineers Journal, 2015

[62] URL: http://www.bioniklabs.com/research-development/arke, Accessed on: 14 April 2016

[63] URL: http://techcrunch.com/tag/power-assist-suit/, Accessed on: 10 April 2016

[64] URL: http://www.exoatlet.com/, Accessed on: 10 April 2016

[65] K. H. Low, X. Liu, H. Yu, “Development of NTU Wearable Exoskeleton System for Assistive Technologies”, Proceedings of the IEEE International Conference on Mechatronics & Automation, pp. 1099–1106, 2005

[66] W. Kim, H. Lee, D. Kim, J. Han, C. Han, “Mechanical design of the Hanyang Exoskeleton Assistive Robot (HEXAR)”, IEEE Conference on Control,

Automation and Systems (ICCAS), pp. 479–484, 2014

[67] URL:http://eurlex.europa.eu/legalcontent/EN/TXT/?uri=CELEX%3A32006L0042 , Accessed on: 04 March 2016

[68] URL: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32001L0104, Accessed on: 06 March 2016

[69] URL: http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=51330, Accessed on: 06 March 2016

[70] URL: http://www.iso.org/iso/catalogue_detail?csnumber=51528, Accessed on: 14 March 2016

[71] URL: http://www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID:1245, Accessed on: 07 April 2016

[72] URL: http://www.iso.org/iso/catalogue_detail?csnumber=38193, Accessed on: 14 March 2016

[73] H. A. Quintero, R. J. Farris, M. Goldfarb, "A Method for the Autonomous Control of Lower Limb Exoskeletons for Persons With Paraplegia", Journal of medical devices, Vol. 6, No. 4, 2012

[74] Y. Zhu, J. Yang, X. Zang, J. Zhao, "Design and evaluation of a parallel series elastic actuator for lower limb exoskeletons", IEEE International Conference on Robotics & Automation, pp. 1335-1340, 2014

[75] A.B. Zoss, H. Kazerooni, A. Chu, "Biomechanical design of the Berkeley lower extremity exoskeleton (BLEEX)", IEEE Transactions on Mechatronics 11, Vol. 11, No. 2, pp.128–138, 2006.

[76] D. P. Ferris, C. L. Lewis, "Robotic Lower Limb Exoskeletons Using Proportional Myoelectric Control", 31st Annual International Conference of the IEEE EMBS Minneapolis, pp. 2119-2124, 2009

[77] F. Casolo, S. Cinquemani, M. Cocetta, "On active lower limb exoskeletons actuators", International Symposium on Mechatronics and its Applications, 2008

[78] A. Yildiz, O. Kopmaz and S. T. Cetin, "Dynamic modeling and analysis of a four-bar mechanism coupled with a CVT for obtaining variable input speeds", Journal of Mechanical Science and Technology, Vol. 29, No. 3, pp.1001-1006, 2015

[79] G. Julió, J.S. Plante, "An experimentally-validated model of rubber-belt CVT - mechanics", Mechanism and Machine Theory, Vol. 46, No. 8, pp.1037-1053,

2011
[80] N. Srivastava, I. Haque, "A review on belt and chain continuously variable transmissions (CVT): Dynamics and control", Mechanism and Machine Theory, Vol. 44, No. 1, pp. 19-41, 2009
[81] G. Carbone , L. Mangialardi, G. Mantriota, "A comparison of the performances of full and half toroidal traction drives", Mechanism and Machine Theory, Vol. 39, No. 9, pp. 921-942, 2004
[82] M. Delkhosh, M. Saadat Foumani, M. Boroushaki, M. Ekhtiari, M. Dehghani, "Geometrical optimization of half toroidal continuously variable transmission using particle swarm optimization" , Scientia Iranica Transactions B: Mechanical Engineering, Vol. 18, No. 5, pp.1126-1132, 2011
[83] O. S. Cretu, R. P. Glovnea, "Constant Power Continuously Variable Transmission (CP-CVT): Operating Principle and Analysis", Journal of Mechanical Design, Vol. 127, No. 1, pp. 114-119, 2005
[84] J. Carter, L. McDaniel, C. Vasiliotis, "Use of a Continuously Variable Transmission to Optimize Performance and Efficiency of Two-Wheeled Light Electric Vehicles (LEV)", EET-2007 European Ele-Drive Conference, 2007
[85] P. Spanoudakis, N. C. Tsourveloudis, "On the Efficiency of a Prototype Continuous Variable Transmission System", Mediterranean Conference on Control & Automation, pp. 290-295, 2013
[86] J. Kim, F. C. Park, Y. Park, M. Shizuo, "Design and analysis of a spherical continuously variable transmission", Journal of Mechanical Design, Vol. 124, No. 1, pp. 21-29, 2002
[87] D.W. Clausen, "Scotch Yoke", U.S. Patent 2366237, Jan.2, 1945
[88] M.P. Greene, "Four-Bar linkage knee analysis", Orthot Prosthet, Vol. 37, No. 1, pp. 15-24, 1983
[89] D.A. Hobson, L.E. Torafson, "Computer optimization of polycentric prosthetic knee mechanisms", Proceedings of the Third Applied Mechanisms Conference, 1973
[90] J.L. Pons, J.C. Moreno, F.J. Brunetti, E. Rocon, "Lower-Limb Wearable Exoskeleton", Rehabilitation Robotics, Sashi S Kommu, 2007
[91] A. Yildiz, O. Kopmaz, S. T. Cetin, "Dynamic modeling and analysis of a four-bar mechanism coupled with a CVT for obtaining variable input speeds", Journal of

Mechanical Science and Technology, Vol. 29, No. 3, pp.1001-1006, 2015

[92] C. Kirtley, “Introduction: Theory and practice in gait analysis” 2006

[93] R. V. Rao, V. J. Savsani, D. P. Vakharia, “Teaching–learning-based optimization: A novel method for constrained mechanical design optimization problems”, Computer-Aided Design, pp. 303-315, 2011.

APPENDIX I: PLAGIARISM REPORT

turnitin

Digital Receipt

This receipt acknowledges that Turnitin received your paper. Below you will find the receipt information regarding your submission.

The first page of your submissions is displayed below.

Submission author:	Ashish Singla
Assignment title:	ME_Thesis_10 words
Submission title:	Baltej Thesis
File name:	2016-Baltej-Thesis-Final.pdf
File size:	2.38M
Page count:	67
Word count:	16,969
Character count:	89,847
Submission date:	27-Jun-2016 05:02PM
Submission ID:	686666061

Chapter 1

Introduction

Elderly people tend to lose their independence and have to depend on others for their basic necessities and for carrying out essential daily chores. They require support for local mobility from one place to another, e.g. crutches, wheelchair, walkers etc. All these conventional methods, as shown in Fig. 1.1 fail to provide independence to the user and they have to rely on someone else. Electrically powered walkers or rehabilitation devices are also available but these devices are not very effective. They could not solve basic problems faced during the use of these devices even if the people do not use the devices but employ an assistant or a family member for helping them.

Fig. 1.1 Conventional personal mobility solutions [7]

The major problems faced by elderly people are:

- inability to sit, stand, perform transfers and to walk
- need for personal assistance at home
- risk losing independence
- reduced quality of life
- financial problems to employ carers

To eradicate this problem of dependency and to give elderly people an autonomous mobility solution, robotics came into rescue. A wearable robotic device is the new

1

Baltej Thesis

ORIGINALITY REPORT

6%	3%	4%	1%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Ryder, Matthew C., and Frank Sup. "Leveraging gait dynamics to improve efficiency and performance of powered hip exoskeletons", 2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR), 2013. Publication	1%
2	www.clawar.org Internet Source	1%
3	HERMAN, CAROL. "MEDICAL DEVICE STANDARDS – WHY THEY ARE SO IMPORTANT", Adaptive Mobile Robotics, 2012. Publication	1%
4	Rao. "Introduction to Optimization", Engineering Optimization, 07/02/2009 Publication	1%
5	Yildiz, Ahmet, Osman Kopmaz, and Sevda Telli Cetin. "Dynamic modeling and analysis of a four-bar mechanism coupled with a CVT for obtaining variable input speeds", Journal of Mechanical Science and Technology, 2015. Publication	<1%

6	VIRK, GURVINDER SINGH. "INTERNATIONAL ROBOT SAFETY STANDARDISATION", Adaptive Mobile Robotics, 2012. Publication	<1%
7	repositorio.ipcb.pt Internet Source	<1%
8	www.kau.edu.sa Internet Source	<1%
9	www.afsec-africa.org Internet Source	<1%
10	www.amhzconsultancy.com Internet Source	<1%
11	Submitted to Keiser University Student Paper	<1%
12	eu-robotics.net Internet Source	<1%
13	Submitted to University of Bradford Student Paper	<1%
14	www.iec.ch Internet Source	<1%
15	VIRK, GURVINDER SINGH, and SEUNGBIN MOON. "SAFETY FOR EMERGING SERVICE ROBOTS", Field Robotics - Proceedings of the 14th International Conference on Climbing and Walking Robots and the	<1%

Support Technologies for Mobile Machines, 2012.
Publication

16	Submitted to Stevenson College Edinburgh Student Paper	<1%
17	www.obcompman.com Internet Source	<1%
18	Submitted to 9659 Student Paper	<1%
19	epubl.luth.se Internet Source	<1%
20	surgrob.blogspot.hu Internet Source	<1%
21	www.diee.unica.it Internet Source	<1%
22	www.next2cents.com Internet Source	<1%

EXCLUDE QUOTES	ON	EXCLUDE MATCHES	< 10 WORDS
EXCLUDE BIBLIOGRAPHY	ON		