A THESIS REPORT
On

CVT Based Design of a Knee Exoskeleton to Provide Partial Assistance During a Normal Walking Gait Cycle

Submitted in partial fulfilment of the requirement

for the award of degree of

Master of Engineering
in
CAD/CAM Engineering

Submitted by

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DECLARATION

I hereby declare that work done in this thesis report entitled, "**CVT Based Design of a Knee Exoskeleton to Provide Partial Assistance During a Normal Walking Gait Cycle**" submitted towards partial fulfilment of requirement for award of **Master of Engineering degree** in **CAD/CAM Engineering** in **Mechanical Engineering Department** of **Thapar University**, **Patiala**, is an authentic record of work carried out by me under the supervision and guidance of **Dr. Ashish Singla**, **Assistant Professor** of **Mechanical Engineering Department**, **Thapar University**, **Patiala**.

This matter embodied in this thesis has not been submitted in part or full to any other university or institute for the award of any degree.

DATE: 22/08/17 **GAURAV GARG**

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

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This report is completed with prayers of many and love of my family and friends. However, there are a few people that I would like to specially acknowledge and extend my heartfelt gratitude who have made the completion of this report possible. With the biggest contribution to this report, I would like to thank Assistant Professor **Dr. Ashish Singla** had given me his full support in guiding me with stimulating suggestions and encouragement to go ahead in all the time of the report.

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ABSTRACT

According to population statistics it is estimated that the people aging more than 65 years will rise to almost 98 million in the next 40 years which fosters the need of advancement in technology that can help old people in maintaining their independence in terms of mobility and strength. For this reason researchers have developed many exoskeleton devices which use actuators and sensors to help the people in sitting, standing and walking.

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 torque range data for the optimization purpose is taken from the experimental results from the Swedish group. 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 and observations form KINECT sensor. 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.

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1. Gaurav Garg, Baltej Singh Rupal, Ashish Singla, Gurvinder Singh Virk, "**Actuation Mechanism for Knee Joint of a Powered Lower Limb Exoskeleton for Torque Variation and Motion Reversal**", 2017.
   [Communicated in **'Advances in Mechanical Engineering'– SAGE Journal**]

Chapter 1

Introduction

BY 2060, the study estimates that old people aging above 65 years of age will number up to 98 million [1] which will be almost thrice as compared to current statistics. With that numbers rising to such a great value will result in increasing problems of mobility as elder people have to depend on others or supporting equipment which result in reduced level of their independence.

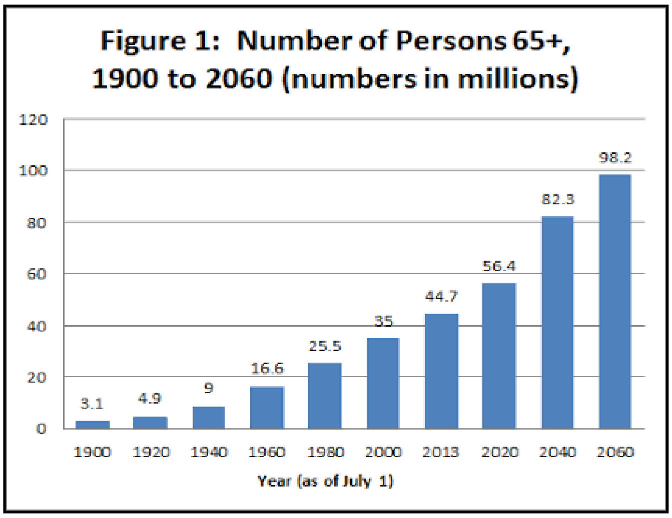


Fig. 1.1: Population Statistics [URL: www.aoa.gov]

The study reveals that one half of the total population of elders is affected by problem called arthritis, which is caused as effect of standing straight and upright throughout life. The concept of 'Off legs' refers to the elderly patients who were previously able to walk and move actively without any problem but due to sudden deterioration because of some disease or infection in older age, they lose their mobility.

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 [2] is the new technology which eradicates these problems and gives a sense of satisfaction to the elderly people.

Losing mobility affects lifestyle to a great extent. It weakens the quality of life, less acceptance in society and greater likelihood of social isolation.

In order to improve the ability of elders to walk properly, various methods of treatment are proposed which helps in effective rehabilitation. Wheelchairs, supporting sticks and stands, etc. are some of the conventional means as shown in Fig. 1.2, but these have some limitations. Wheelchairs cannot be accessed at all places, e.g. stairs, and also it cannot give access to user for walking. Moreover some expensive rehabilitation techniques have been developed which helps in regaining the mobility to some level by constant application of therapies at regular time intervals.

Fig. 1.2: Conventional methods [Source: www.dreamstime.com/stock-photography-person-handicapped-wheelchair-image38043902]

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 [3] 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 1.3 shows the basic components of an exoskeleton device.

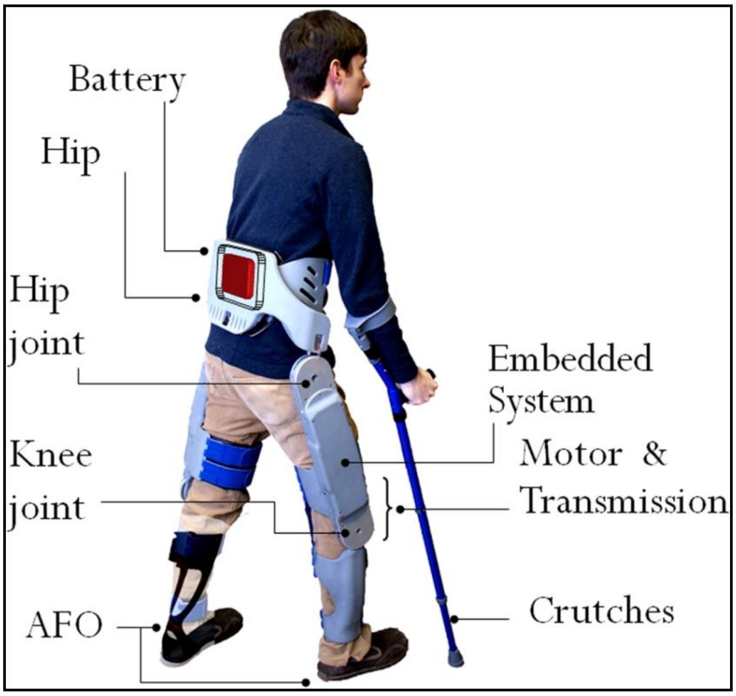


Fig. 1.3: Exoskeleton worn by a human bring showing its all major parts [H. A. Quintero, 2012]

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 [5] presented in Fig. 1.1 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.

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 [6]. 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 [7-11] 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.

Background

Spinal Cord Injury

There are different number of ways in which the classification of spinal cord injuries can be done as shown in Fig. 1.4. The first is the level of the injury. For those classified as paraplegics, the lower part of human body is affected by the disability. Quadriplegia, [12] is the level in which the arms and legs are affected by disability.

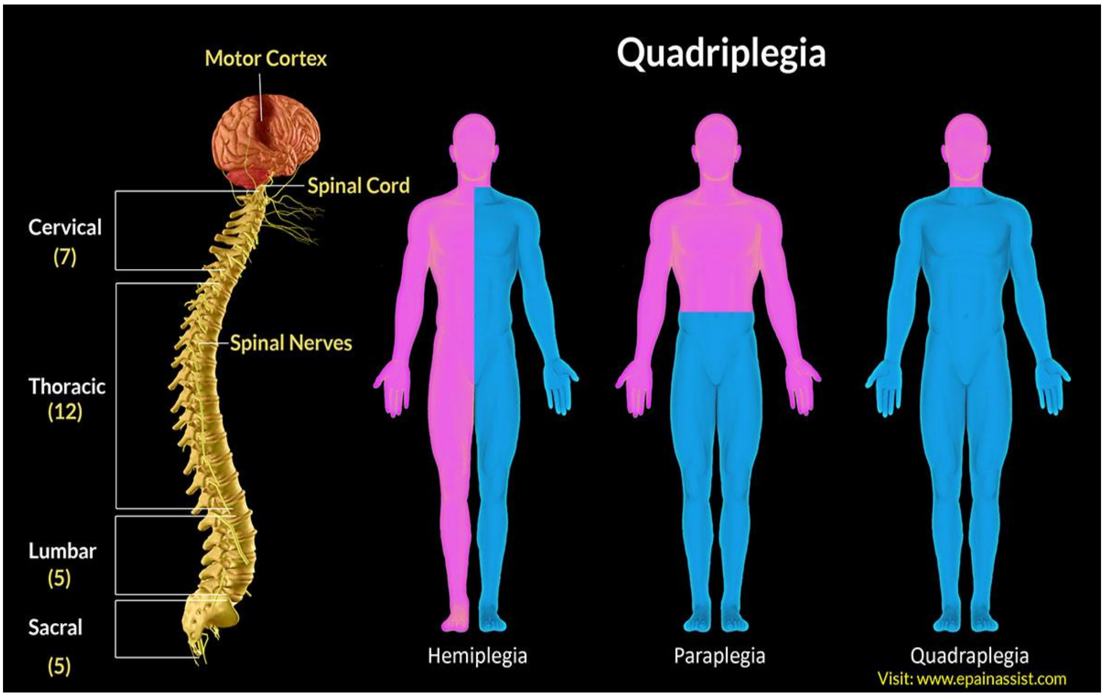


Fig. 1.4: Types of Paralysis - colour area indicates area of paralysis [https://www.epainassist.com/images/quadriplegia.jpg]

Patients, who are suffering from spinal cord injury, also have to deal with secondary injuries, such as bed sores, increased tendon reflex activity and hypertonia, failure of respiratory functions, osteoporosis, and fractures, which results in reducing their life-span. These injuries occur due to their inability to move around or stand up to increase blood flow and relieve pressure points. All these kind of medical instabilities can be reduced or eliminated by enhancing the ability of locomotion. Patients need to exercise regularly and adopt rehabilitation techniques [13] and avoid spending too much time on wheelchairs. An exoskeleton will allow the patient to move around as well as remain upright, increasing blood flow to the lower body.

Stroke

Stroke is a type of injury that results when supply of blood to the brain is disturbed. The blood being deficient of oxygen and other nutrients falls to damage and death of brain cells in short interval of time [14]. This defect results in partial or full paralysis of one or more limbs of human body because of dysfunction of the contralateral affected area on the brain. In case the lower part of the body is affected from paralysis, a rehabilitation treatment is required to restore gait function and in order to regain the independent walking capacity.

Various types of robotic platforms are developed in the last few years which speeds up the process of recovery in case of stroke patients [15-16]. The effectiveness of robotic rehabilitation in comparison with manual therapy in patients suffering from stroke has also been the topic of research in recent times. Robotic rehabilitation is a research field that tries to understand the rehabilitation process and improve it by applying robotics devices. This rehabilitation process develops therapies using robots as therapy aids devices. Gait training equipments can be categorized into following two groups: *end effectors* and *powered exoskeletons* [17]. The first category includes devices with end-effectors in which, footplates are mounted below the feet of patient. In this simulation of both swing and stance phase of gait cycle is performed. It is demonstrated in the work of Hesse et al. which shows a device for repetitive practice of walking on floor and climbing of stairs for stroke patients.

The second category includes more advanced devices - powered exoskeletons. With the advent of technology the robotics have developed a great solution in the form of Exoskeletons which are defined as external human wearable structures that aid in improving efficiency of walking, lifting of load, etc. The term exoskeleton is derived from the Greek words “exo” and “skeletos” which means outer skeleton [18]. Powered exoskeletons are wearable robots attached to the wearer’s limbs, in order to improve their locomotion. These should be compliant with the users’ movements and deliver at least part of the power necessary to accomplish the desired motions.

Major advantages:

- Prevents muscle atrophy by daily use and enhance recovery in case of damage.
- Increase the autonomy of person by allowing the people to do things on their own without anybody’s help.
- Improving the psychological state of user.
- It is not necessary to adapt the environment of the person to use an exoskeleton.
- Reduces the energy required to move the joints (knee/hip/ankle) as the load is taken by the suit.
- Specific joints/muscle groups can be targeted for therapy. (using rehabilitation exoskeletons)

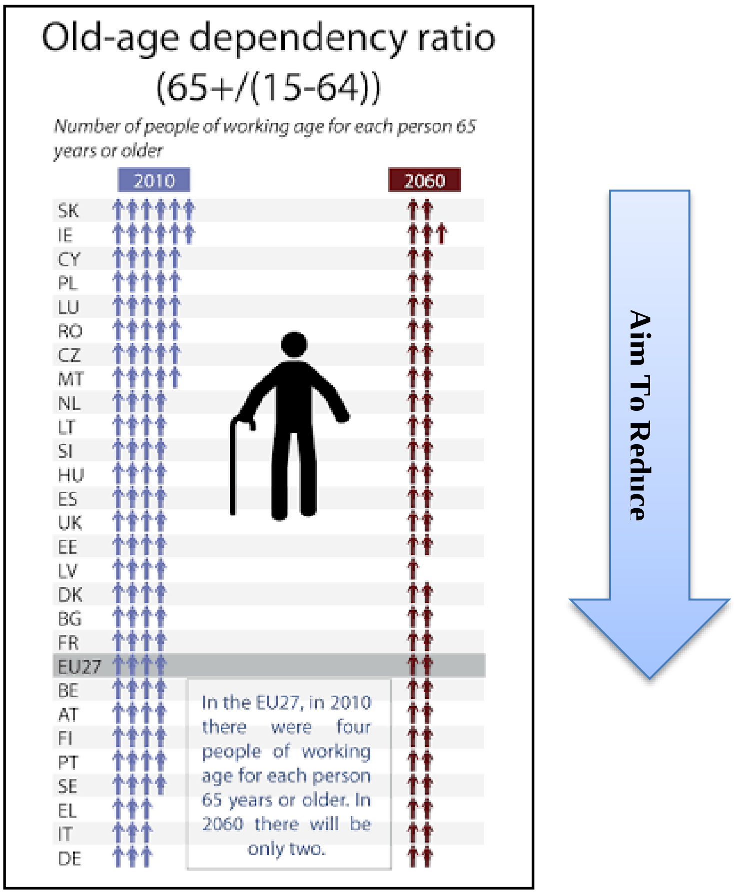


Fig. 1.5: Dependency Ratios

[http://www.un.org/en/development/desa/population/publications/pdf/popfacts/PopFacts_2014-4.pdf]

These exoskeletons are greatly helpful in replacing all those existing sources because they not only provide better and modern control but also provides freedom to the user as by use of such devices, elder people will no longer depend on others, frequency of which is shown in Fig. 1.5, for their mobility and could perform routine functions easily [19]. Continuous development and advancement in this field is being done to improve design, control and costs of these systems so that everyone could take its advantages.

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 [20]. 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 [21-23] 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 [24]. 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 [25].
- 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 [26].
- 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 [27]. 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 [28] 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 [29-30] 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 a holistic idea about the current state of the technology and the directions for the research work. 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 3**, 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 addition, various design considerations are discussed which can be followed keeping in mind the area of use for exoskeleton. 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 4**, 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 5**, further modification in the proposed design of hybrid mechanism is done. In order to deal with one major issue of exoskeleton i.e., weight, use of single CVT is made to drive both the knee joints. Time phase between two legs is the key challenge in such a design, on achieving which a great improvement in design is observed and outputs best results.

In **Chapter 6**, 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 Introduction

In this literature survey, the state of art of lower limb exoskeletons and different type of CVTs are reviewed according to different categories based on which a brief classification layout will be presented. This study is restricted to the ones designed for elderly people and gait assistance and excluded the others like the ones designed for military and load carrying purposes. Different methods of gait assistance and torque variation will be discussed and then some new concepts will be discussed.

2.2 History

Hardiman*:* It was the first modern exoskeleton of its kind as shown in Fig. 2.1. It was developed by General Electric in 1965. It allowed the human beings to lift 680 kg. User feels only 1 kg weight when he lifts 25 kgs. Due to control problems, it was never tested. Then only one arm prototype was tested. Arm was capable enough to lift a weight of 340 kgs and user felt only 13.6 kgs. The arm weighed 750 kgs, which made this project impossible and the final project was limited [18]. Hardiman's size, weight, lack of stability and power supply problems limited it only to a prototype.

Fig. 2.1: Hardiman [Dollar and Herr, 2008]

2.3 Classification

The Fig. 2.2 shows the basic classification of exoskeletons-

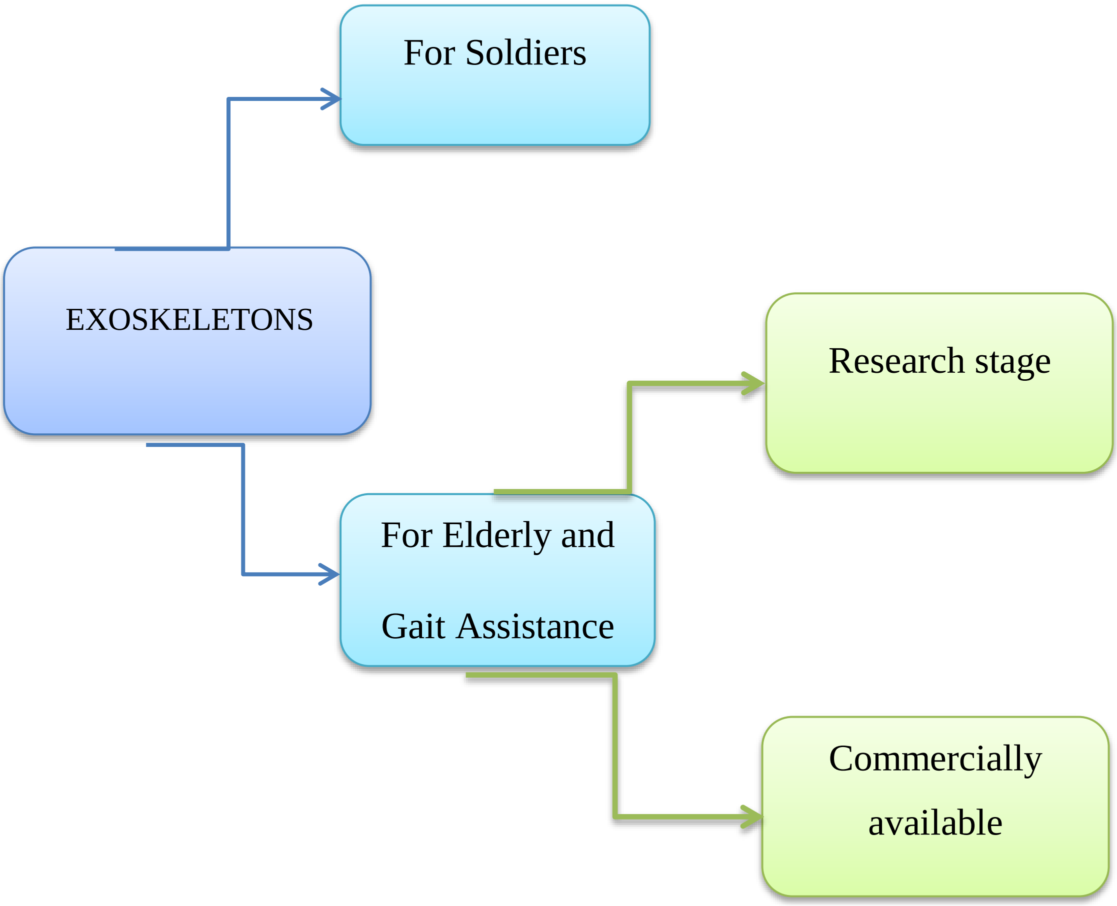


Fig. 2.2: Classification of exoskeletons

2.3.1 Exoskeletons for Soldiers

These are the exoskeletons which are used in military purposes and as force multipliers, as shown in Fig. 2.3. Military exoskeletons [31] are intended to be used by soldiers in the battlefield or in rescue activities. They are aimed to augment the strength and endurance of soldiers, making possible for them to carry heavy loads, walking longer distances, etc. Military exoskeleton development has been basically promoted by DARPA (Defense Advanced Research Projects Agency), an agency of the United States Department of Defense responsible for the development of new technologies for military use. Two main projects, developed respectively by SARCOS in Utah and Berkeley in California, have been funded by DARPA.

Some of the major exoskeletons that are developed under this category are discussed as follows in the chart.

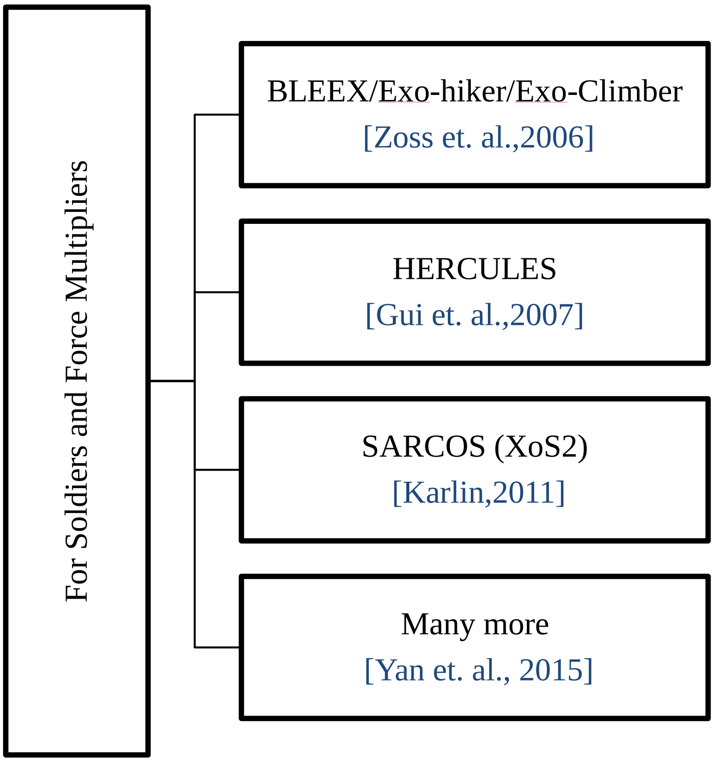


Fig. 2.3: Load carrying exoskeletons

(a) BLEEX (Berkeley Lower Extremity Exoskeleton)

University of California, Berkeley is the developer of this exoskeleton [32]. It is a load carrying augmentation device, designed specifically for US soldiers, as shown in Fig. 2.4. Hydraulic power has magnitude of up to 2.27 kW, 220 Watts of electrical power. The total weight of complete system is around 45.35 kg. Few limiting characteristics of this exoskeleton are high noise device and a minimal payload as compared to weight ratio of the system. The complete device weighs 14 kg.

Fig. 2.4: BLEEX [Dollar and Herr, 2008]

In case of any failure occurrence this could result in major threat to the wearer because of its weight.

(b) Hercule

RB3D, an engineering group in France led to the development of exoskeleton named as Hercule, as shown in Fig. 2.5. Military procurement agency DGA was the source of funding towards this development. The final model of this device justified its name as it showed the capacity to carry 20 kg of weight with each arm, and further research expectations are to increase this capacity up to 100 kg. It is electrically powered. The life of its Li-Ion batteries is proved enough to walk 20 km at a moving speed of 4km/h, a regular walking place, while carrying 100 kg.

Fig. 2.5: Hercules [army-technology.com, 2012]

(c) Exo Climber

This exoskeleton, as shown in Fig. 2.6, was constructed in October 2005 [33]. As the name suggests this exoskeleton suit was proved useful in conquering steep slopes and quick climbing of stairs along with application of load by the user. It weighs 50 lbs including power unit and on board computer. The wearer feels no vertical load with weight up to 150 lbs. It is as quite as an office printer. Mission range is at least 600 foot ascent per pound of battery while carrying 150 lbs payload. Small fuel cells can be optional energy source.

Fig. 2.6: Exo Climber [http://bleex.me.berkeley.edu]

(d) SARCOS Exoskeleton

It is powered exoskeleton which provides autonomous power supply to the user [34]. It uses the concept of rotary hydraulic actuation. These rotary hydraulic actuators are located on the power joints of the user. This is a very powerful suit which is basically used for military purposes. The SARCOS exoskeleton as shown in Fig. 2.7 uses a variety of sensors for determining force and position in the system.

Fig. 2.7: SARCOS [Karlin, 2011]

2.3.2 Exoskeletons for elderly people and gait assistance

Current Gait Training Devices

Current gait training methods can be divided into two categories. One category is traditional clinical treatments. The second category includes the newer treatments, mostly based on robotic systems.

(a) Manual Gait Training and Braces

Traditional clinical gait training usually begins with manual gait training. This is done using a body weight support system over a treadmill. In this system, one physical therapist helps support the user’s body and balance while two others move the legs in a walking motion. This can be seen in Fig. 2.8. During manual gait training, two therapists move the patient’s legs while one supports the patient’s hips and aids with weight transfer. This therapy is done over a treadmill with a body weight support harness. While this is effective for initial training, it is tiring for therapists and requires two or three therapists to support a single gait training session [35].

Fig. 2.8: Manual gait training [http://www.physicaltherapyjournal.com/content/80/7/688.full]

Once a patient has sufficiently progressed, he may move on to over-ground gait training. This is usually done using braces to support the weak joints. Braces vary in length based on what joints need support and range from HKAFOS (hip knee ankle foot orthosis) to KAFOS (knee ankle foot orthosis) to AFOs (ankle foot orthosis). Over-ground training is usually done in parallel bars for safety and support. This method allows the patient practice walking, but requires a lot of energy which limits the number of steps he can take in one session [36-37].

(b) Treadmill-Based Robots

In the second category of gait training devices, there are more robotic options for spinal cord injury subjects. These devices, whether over-ground or treadmill based, provide increased repetition of gait as opposed to manual treadmill training. They also provide mobility with lower energy expenditure than traditional braces [38].

One of the most widely used treadmill-based devices is **Lokomat**, which is built by Hocoma, as shown in Fig. 2.9. Lokomat features a natural and repeatable gait pattern, intense training, motivation through biofeedback, and sensor information from the user’s interaction with the machine Invalid source specified. Lokomat has been used by numerous hospitals with positive results. Studies have shown that functional abilities increased more in sub-acute spinal cord injury patients who used Lokomat as opposed to those who did not. Other studies likewise indicate that this training may be beneficial to those who use it. However, the Lokomat does require a large amount of floor space in a rehabilitation center to be used.

Fig. 2.9: LOKOMAT [Colombo, G., 2000]

A second treadmill-based rehabilitation robot is **LOPES**. LOPES, as shown in Fig. 2.10, is developed by the University of Twente. The robot has multiple degrees of freedom including knee and hip flexion and extension for walking. It also has hip abduction and adduction for balance training, which supported by horizontal translation of the treadmill support rig for safety. The pelvis also has vertical translation freedom for natural hip motion. This robot has undergone clinical tests to determine efficacy and safety for chronic stroke patients. The study was too limited to make general conclusions but researchers feel that it offers a method by which stroke patients can recover some function.

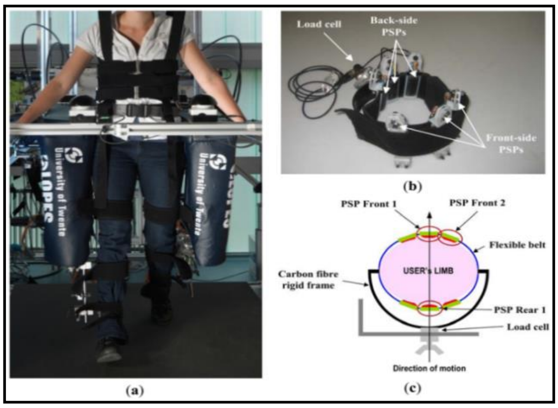


Fig. 2.10: LOPES [Geonea, 2015]

While treadmill-based robots have been able to provide consistent therapy for many patients, their use is limited. Because they are coupled to a treadmill and the joints are moved for the user, the user may become passive in the rehabilitation. For this reason, many people have focused on making interactive displays to help maintain focus and engagement while undergoing rehabilitation. Furthermore, the user is not responsible for balance, which can be an important skill to develop during gait rehabilitation. For rehabilitation clinics, space availability can be a concern, so treadmill based robots, which take up valuable floor space, may be too large.

(c) Mobile Robots

There are many benefits to mobile robots for gait training. Their smaller size and increased involvement from the user make them of interest to clinics. However, to the users, the vision of using these at home or outside of the clinic is the main draw. Mobile robots offer the ability to continue gait training or provide gait support outside of the clinic. The increased time with the robot may yield better rehabilitation results. For those who rely on wheelchairs for mobility, the mobile robots provide a means to move through their daily lives while standing.

There are a few companies that are developing mobile exoskeletons for rehabilitation and mobility, much like the one discussed in this report. They are **Rex** by Rex Bionics, **HAL** by Cyberdyne; **ReWalk** by Argo Medical Technologies and many others. While each of these has varying features, their overall goal is to provide a mobile platform to assist walking [23-25, 39-42].

There are also few exoskeletons in this category which are developed at research platform and are not commercialized yet. They are either in progressing stage or are being modified to cut down their costs, weight, etc. Their overall aim is also to provide mobility to the needy. Few of them are **Vanderbilt** by Vanderbilt University, **Elegs** by Berkley Bionics, and **Nurse assisting exoskeleton** by Kanagawa Institute with many more in the category [43-44].

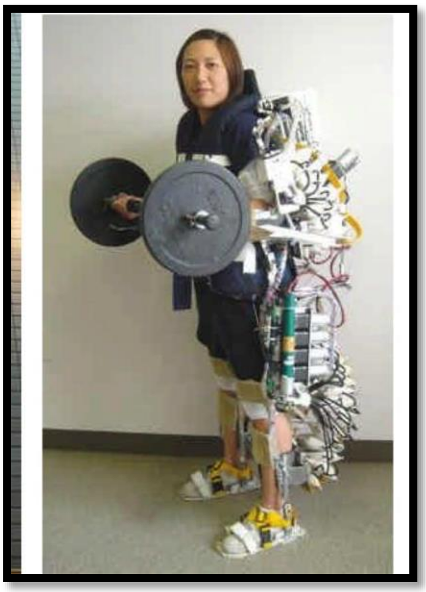
Table 2.1: Different types of exoskeletons

Type	Description
	Rex, as shown in Fig. 2.11, is a mobile exoskeleton for use by spinal cord injury

 Fig. 2.11: REX [www.rexbionics.com]	patients and “manual wheelchair users who can self-transfer and operate hand controls”. Rex’s outstanding feature is its stability. Currently among all available exoskeleton prototypes for both in research and commercial market, the only exoskeleton that can support itself without any crutches is the REX. Rex also assists with the lateral weight shift while walking, which is not provided for in the other mobile robots. It has joystick control rather than sensors. Each leg of this exoskeleton possesses 5 DOF the hip has 2, the knee holds 1 DOF and ankle again has 2 DOF. Multiple DC motors of brushed type act as actuators for the respective DoFs. Device cannot weight more than 38 kg and it allows user to lift maximum of 100 kg of load. However, Rex is bulky and slow.
 Fig. 2.12: HAL [Source: Cyberdyne]	HAL, as shown in Fig. 2.12, is developed by Tsukuba University and Cyberdyne, both in Japan. HAL utilizes biofeedback through EMG signals from the surface of the skin, which makes it applicable for some injury types where muscle signals can still be read. These are then translated into the motion, allowing the user to move. HAL comes in multiple versions, and some versions include both upper- and lower-body components. The lower body model of the device weights about 15 kg and the full body model about 23 kg. It is battery operated and has autonomy of approximately two and a half hours. Hip and knee joints actuators are based on DC servo

	motors and Harmonic Drive gears, while the ankle joint is passively controlled. HAL has a control unit carried in a backpack by the user. This unit runs a Linux operational system and communicates to a remote monitoring computer by wireless Local Area Network.
 Fig. 2.13: ReWalk [www.argomedtec.com]	ReWalk, as shown in Fig. 2.13 is intended for persons with lower limb disabilities that have suffered injuries in the spinal cord. It cannot keep balance control, so the user should always be supported by crutches. Agro Medical technologies were the provider or source behind this first ever walking exoskeleton robot. Maximum walking speed is 0.6 m/s and it weighs 20.9 kg. It has battery life of about 8hrs. They have distinguished two different products: ReWalk-I, for institutional use, and ReWalk –P for personal use. ReWalk has undergone trials at the Moss Rehab center, but study results are not yet published. ReWalk provides the user the ability to walk, climb stairs, sit, and stand. The gait appears to have less knee flexion than many other devices.
	Vanderbilt University, as shown in Fig. 2.14, is known as the developer of the famous over ground exoskeleton named as Indego. Indego was designed such that it could be used on integration with a set of standard ankle-foot orthoses. One of distinguishing feature of this exoskeleton from others of its kind was its light weight which is almost half than others, and also its applications can be extracted by

 Fig. 2.14: Vanderbilt Exoskeleton [Clare Hartigan, 2013]	wheelchair operators too. It has a battery life that lasts up to 4hrs. The device weights about 12 kg and, like the other robotics exoskeletons discussed here, it has only hip and knee as actuated joints. The device is powered by brushless DC motors through a 24:1 gear reduction, which provides a maximum continuous torque of 12 Nm for hip and ankle joint. A lithium polymer battery of 29.6 VDD and 3.9 Ah brings one hour of autonomy for continuous walk with the device at a speed of 0.8 km/h.
 Fig. 2.15: eLEGS [Eksobionics]	Ekso Bionics (earlier Berkeley Bionics) , as shown in Fig. 2.15, is a North American company that originally developed exoskeletons for military use. In October 2010 they have unveiled a rehabilitation version called eLEGS (Exoskeleton Lower Extremity Gait System) that in 2011 was renamed as Ekso. Ekso weights approximately 20 kg and has a maximum speed of 3.2 km/h with a battery life of 6 hours. It can execute sit-to-stand and stand-to-sit operations and walk in a straight line. Ekso is currently going under development to become lighter and more adaptable. Clinical trials are on-going in rehabilitation centers in United States. The device can be commanded by a user interface that can control the device step by step.

 Fig. 2.16: Nurse assisting Exoskeleton [Dollar, 2008]	This suit was developed at Kanagawa Institute of Technology in Japan, as shown in Fig. 2.16. In order to make this suit compact and portable, actuators were attached directly by small pneumatic pumps. Some of the facts were not made clear like what attachment procedure is followed and also the properties of the DOFs that are not actuated. There is no mechanical component on the front of the user, allowing the nurse to have direct physical contact with the patient that he or she is carrying. This is an important property for ensuring the comfort and security of the patient.

2.4 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.

The major problem faced by lower limb exoskeletons is the powering issue and the torque variation technique. 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.

Observations from the exoskeleton literature survey leads to following major problems which need to be solved.

- To find an alternative source of battery charging
- To find a suitable device for torque variation

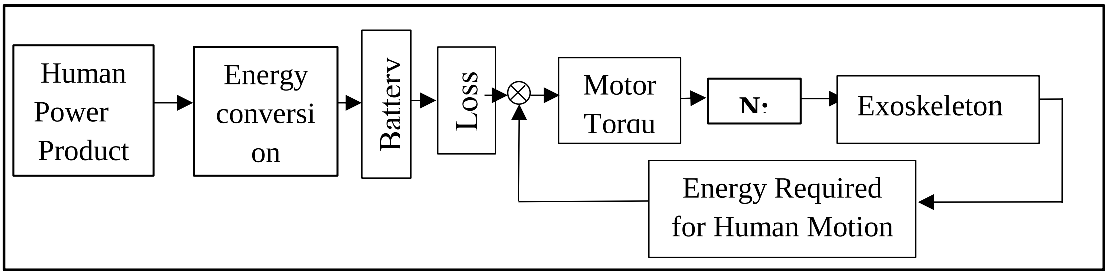


Fig. 2.17: Problem formulation

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 [45], 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 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.

Microcontrollers [46] seems 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 [47]. Hydraulic and pneumatics [48] 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 [49] if miniaturised can be used in exoskeletons. So it is further explored in the next section and its feasibility for exoskeletons is done. Fig. 2.18 shows the brief comparison between various torque control devices.

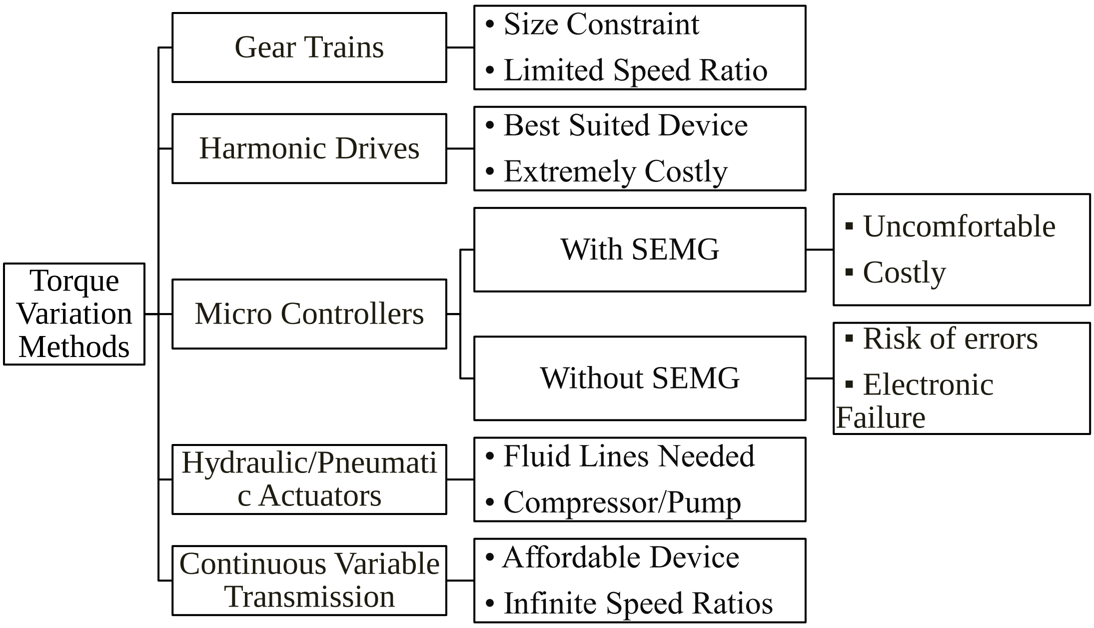


Fig. 2.18: Torque variation methods

2.5 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.

The table below summarises the comparison between the above discussed exoskeletons.

Table 2.2: Comparison of exoskeletons

Suit	**Weight (kg)**	**Actuator Used**	**Battery Type**	**Battery Life**	**Need of Sticks**	**Comfort Level**
REX	38	Brushed DC	-	2 hrs.	No	Medium
HAL	15	DC servo motors	Li. Ion	2.5 hrs.	Yes	High
ReWalk TM	24	DC motors	Rechargeable DC	7-8 hrs.	Yes	Low
Vanderbilt Suit	12	DC brushless	Li. Ion	1 hr.	Yes	Medium
eLEGS	20	Linear actuators	-	6 hrs.	Yes	Low
Nurse Assisting Suit	18	Pneumatic pumps	-	-	No	Low

The crux of the observations extracted from the above literature survey is summarised in the following points:

- The physical structure of the exoskeletons is very large and uneasy to handle for the users. So they avoid such devices and prefer conventional methods.
- The weight of the system adds another hindrance, as it becomes difficult for an elderly person or a paraplegic to wear such a heavy device and feel comfortable in it.
- Size of batteries and the problem of taking the load the batteries on back is a big problem.
- Sticks are still required even after wearing the suit which is a big disadvantage.
- Cost of the systems is too high.

Chapter 3

Design Considerations

3.1 Introduction

In previous chapter, concept of different types of exoskeletons is introduced. In this chapter, different design mechanisms are stated which can be opted while designing an exoskeleton based on various parameters of usage – power, position, speed, etc. Different actuation techniques could also help in achieving variations in design mechanism. These factors plays important role in deciding the output of an exoskeleton in terms of efficiency, range of movement, weight, payload etc. These exoskeletons can be grouped according to following design considerations:

- Based on leadscrew mechanism
- Based on hydraulic actuation
- Based on Series elastic actuation
- Based on Pneumatic Muscles
- Based on Winch actuation

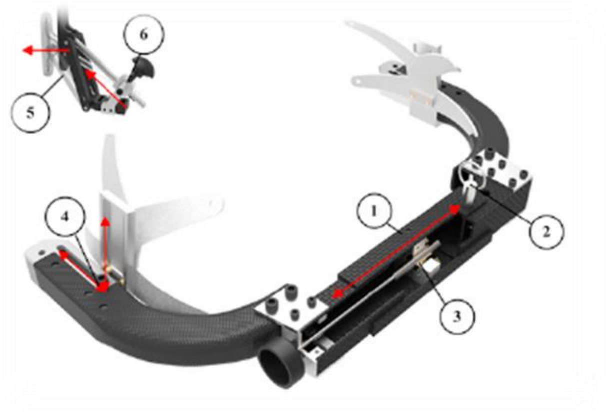


Fig. 3.1 Leadscrew Mechanism [F. Giovacchini, 2015]

(1) The two arms made up of carbon fiber are connected by rear-bar. (2) Regulation is achieved by detachable pin. (3) Fine adjustment is achieved by use of Leadscrew mechanism. (4) Alignment for axes of flexion–extension with help of rails. (5) Interface for supporting back, namely lumbar region. (6) Screw mechanism.

Following subsections describe the characteristics and properties of exoskeletons in general that are affected by the basic design or selection of actuation mechanism.

i) Leadscrew Mechanism- In an exoskeleton, the correct transmission of assistive torque is required. For this, it must provide correct pushing support based on ergonomics at the lumbar region of the user wearing it. Leadscrew mechanism [60] helps establishing this support by making fine adjustments of orthotic shell, which is fixed on rear bar, as shown in Fig. 3.1. Now, this allows the exoskeleton to be worn by subjects of different body dimensions and still resulting in correct transmission of torque required. With this arrangement, it is observed that 50% torque assistance can be provided to the subject at maximum i.e. upto 35 Nm. Such systems are often combined with harmonic drives that allow better control of exoskeleton. Range of motion varies between −30° and 110°, limited by mechanical stop linkages. The gait speed range which results from such design is 2 to 5 km/hr with a payload of not more than 80 kg.

Fig. 3.2: Hydraulic actuation [W. Huo, 2016]

ii) Hydraulic actuation- This specific type allows for smallest actuation for an exoskeleton. This actuation selection results in high specific power but at same time the power consumption is high [61] as compared to electric actuators. This type of actuation can allow for designing an exoskeleton with 7 DOF as shown in Fig. 3.2 [62]. It includes hydraulic cylinders which help to transmit fluid power and transmission of force could be controlled. Such actuation has a benefit of providing torque assistance for full range i.e. 60 Nm. Range of motion for such system is also more than previous one i.e. upto 121^0 and speed range can be increased up to 6-7 km/hr [63].

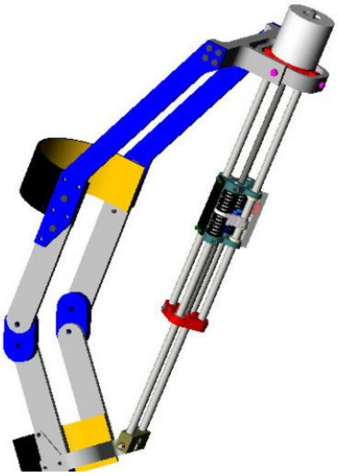


Fig. 3.3: Series elastic actuation [J. E. Pratt, 2004]

iii) Series Elastic Actuator- These types of actuators, as shown in Fig. 3.3, allow for designing exoskeletons that play significant role in relationship between output of the actuator and load. One of significant characteristics' is the weight that is very light in this case, addition to which it provides very less amount of resistance. This actuator has features like- low impedance, high force-fidelity, and good bandwidth which enables better control algorithm. Usually these are mounted on back of user, which gives a stable design but in that case design is restricted only for walking assistance and not for sit to stand motion. Full range of human motion can be achieved for both walking and running with maximum gait speed of 9 km/hr [64].

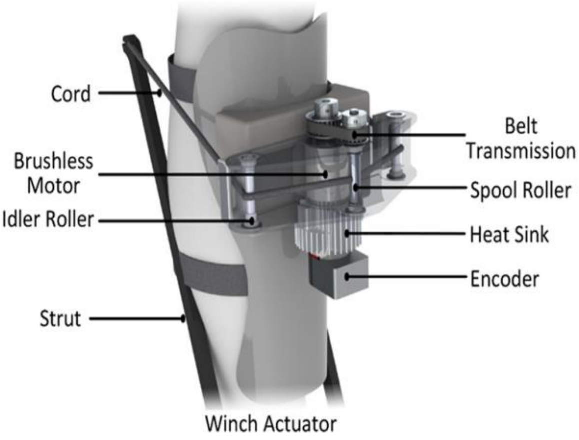


Fig. 3.4: Winch Actuator [L. M. Mooney, 2014]

iv) Winch actuator- This type of actuator is used while designing an ankle exoskeleton. It helps in providing assistive torque of planar-flexion nature about the ankle joint. For this purpose, the role of moment arm is played by struts as shown in Fig. 3.4. It uses a system of wire and spool which is tightened to apply force on the struts. This design results in lower weight and less complexity due to elimination of traditional mechanical transmission as it is done with geometric transmission [66]. Total mass of such system is 4 kg. Torque assistance provided by such a design can be achieved to a level of 80% with gait speed of 5.5 km/hr. The maximum weight of user which was tested wearing this exoskeleton can go up to 84 kg.

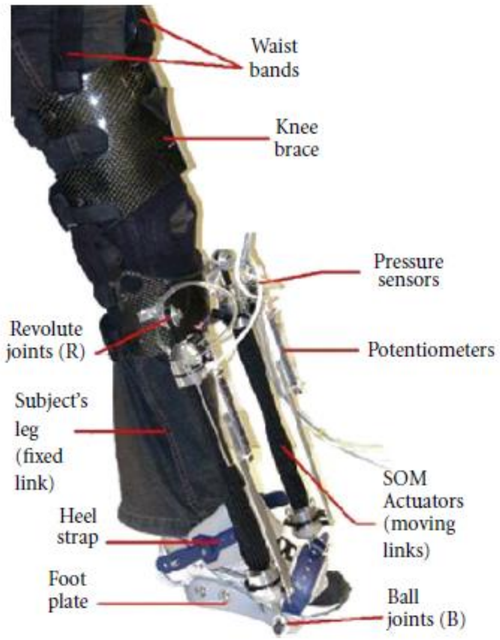


Fig. 3.5: Pneumatic Muscle [L. Wang, 2013]

v) Pneumatic Muscles - These actuators are used in design where less weight of knee joint is desired, like not more than 1.5 kg [68]. This kind of system is labelled as small yet powerful. It provides torque assistance of 15 Nm to leg i.e. up to 50% [69]. Air pumps at micro level are used as power source for such systems so making them little complex. Basic mechanism is same as that of hydraulic, cylinders and piston mechanism is controlled through supply rate of air. Pressure can be controlled which helps to achieve desired results. Such systems are often cheap and easy to implement. Usually designed for knee and ankle exoskeleton as shown in Fig. 3.5 and can handle user weight up to 80 kg.

3.2 Table for Comparison

In this section, effect of different design parameters on an exoskeleton device are summarized in a Table 3.1

Table 3.1: Comparison of different exoskeleton designs on various parameters

Design Factors / Characteristics	**Leadscrew mechanism**	**Hydraulic actuator**	**Series elastic actuator**	**Pneumatic Muscles**	**Winch actuator**
Percentage assistance	50%	100%	NA	50%	80%
Part of lower body	Hip to knee	Full lower body	Hip to knee Ankle	Knee to ankle	Ankle
Range of motion(Degrees)	-30 to 110	Up to 121	NA	up to 120	NA
Gait Speed (km/hr)	2-5	6-7	9	6-7	NA
Weight handled (kgs)	80	More than 100	NA	80	84

3.3 Need for CVT Based Design of Exoskeletons

The Continuously Variable Transmission (CVT) is also 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. 3.6 below classifies CVTs in broad way.

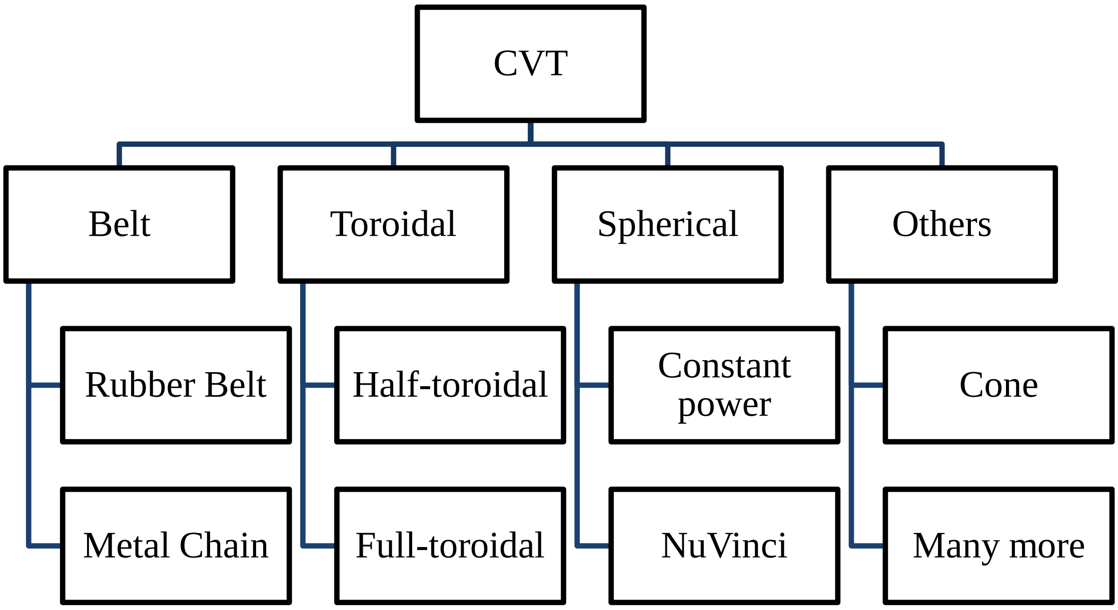


Fig. 3.6: Classification of CVTs

3.4 Types of CVT

3.4.1 Belt CVT

The belt based CVT [50], 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. 3.7. 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.

The system is still effective for small engine vehicles under 1,500 cc, like the drilling machines, as mentioned before. Hence, 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. 3.8 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.

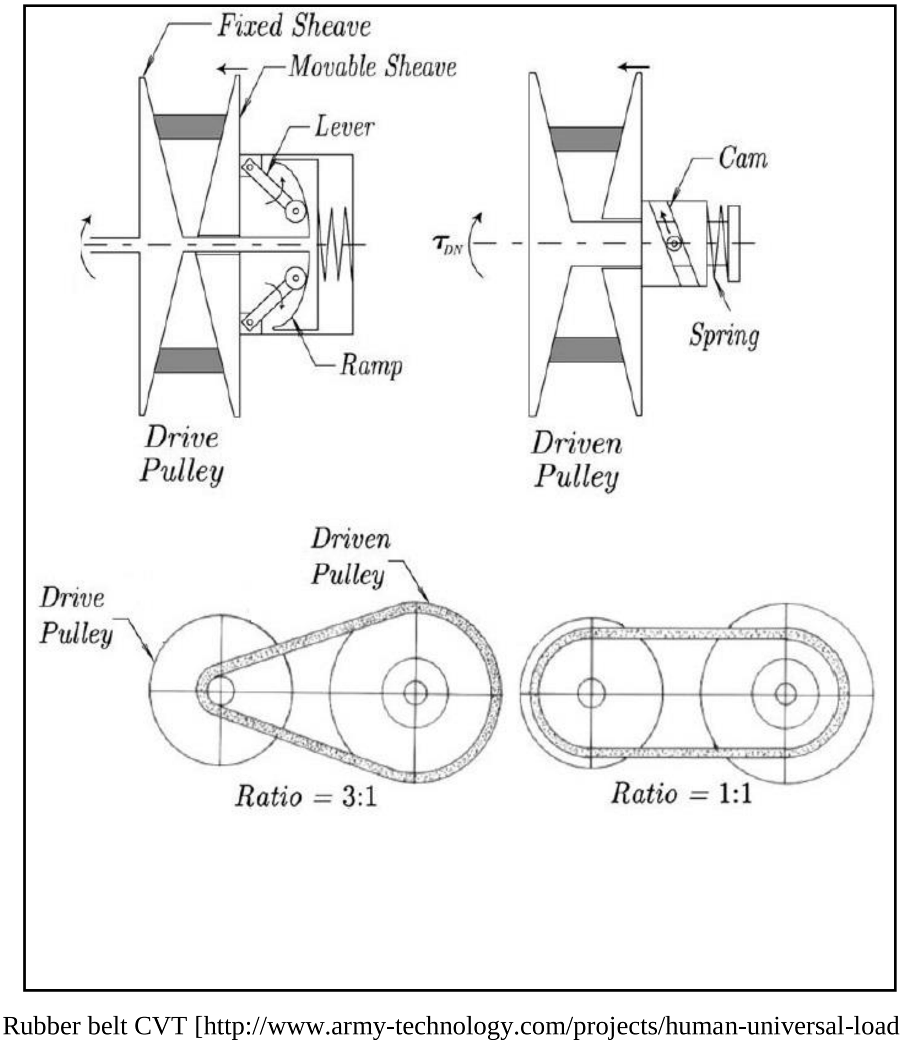


Fig. 3.7: Rubber belt CVT [http://www.army-technology.com/projects/human-universal-load-carrier]

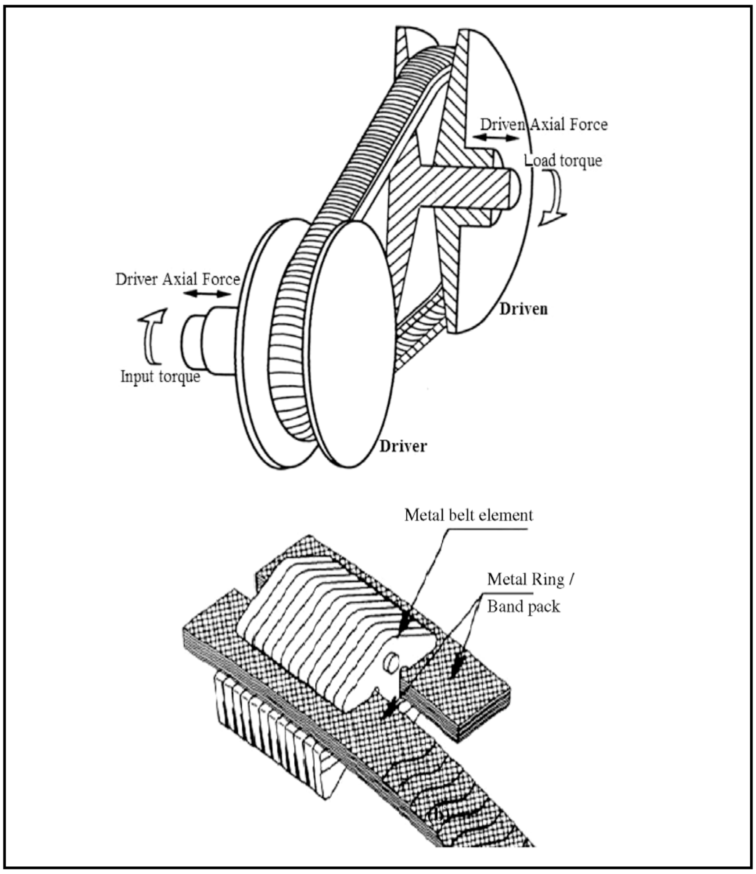


Fig. 3.8: Metal chain CVT [http://bleex.me.berkeley.edu/research/exoskeleton/exoclimber]

3.4.2 Toroidal CVT

Roller based CVT is also known as toroidal CVT [51]. 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 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. 3.9 shows a half toroidal CVT, the operation of half and full toroidal CVT, Fig. 3.10 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.

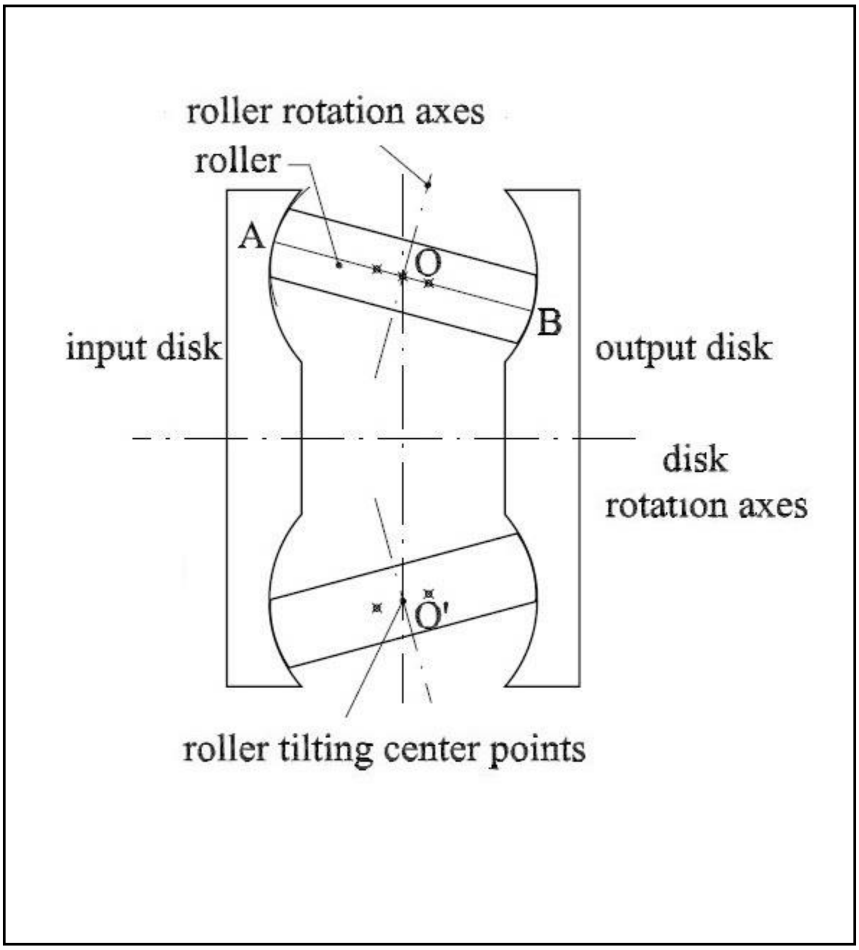


Fig. 3.9: Half-toroidal CVT [http://biology-forums.com/index.php?action=gallery;sa=view;id=9333]

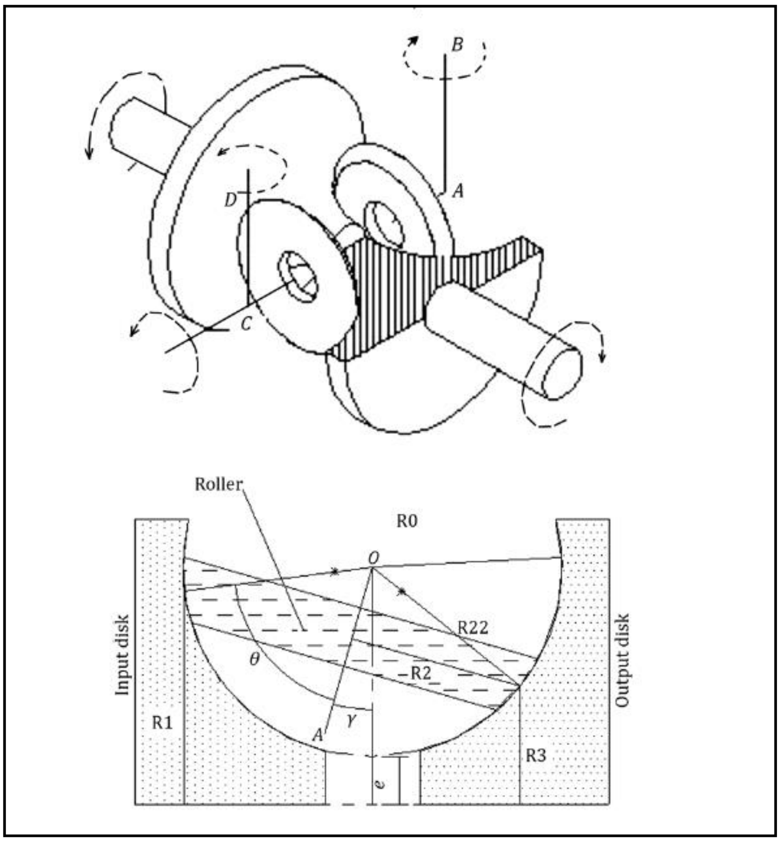


Fig. 3.10: Full-toroidal CVT [http://www.gizmag.com/lockheed-martin-lab-testing-hulc-exoskeleton/16768/]

3.4.3 Spherical CVT

The constant power spherical CVT, also called the CP-CVT [53] 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. 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. 3.11. 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.

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 [34], which is a patent and a commercial device. The constructional features and an outlook of NuVinci is shown in Fig. 3.12 which uses very simple principle of a spherical ball control which changes the output gear ratio, here also control is a big hindrance.

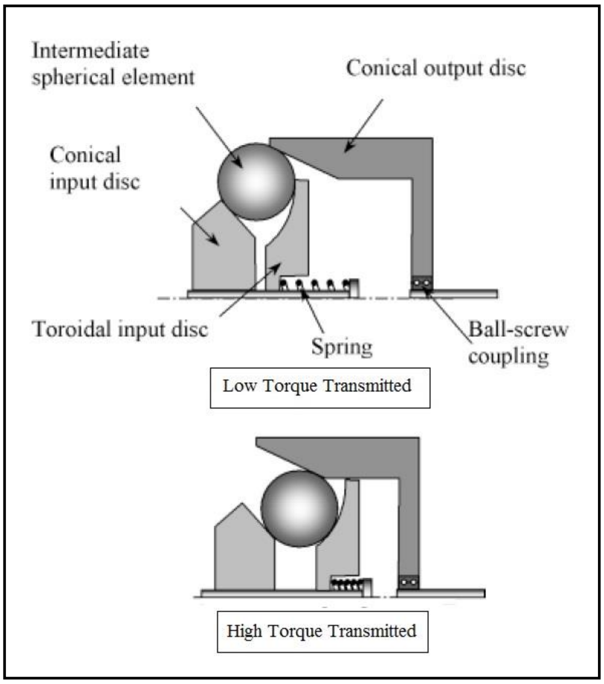


Fig. 3.11: Constant power CVT

[http://www.dailytech.com/From+HULC+to+FORTIS+the+Evolution+of+Lockheed+Martins+Incredible+Exosuit/article36421c.html]

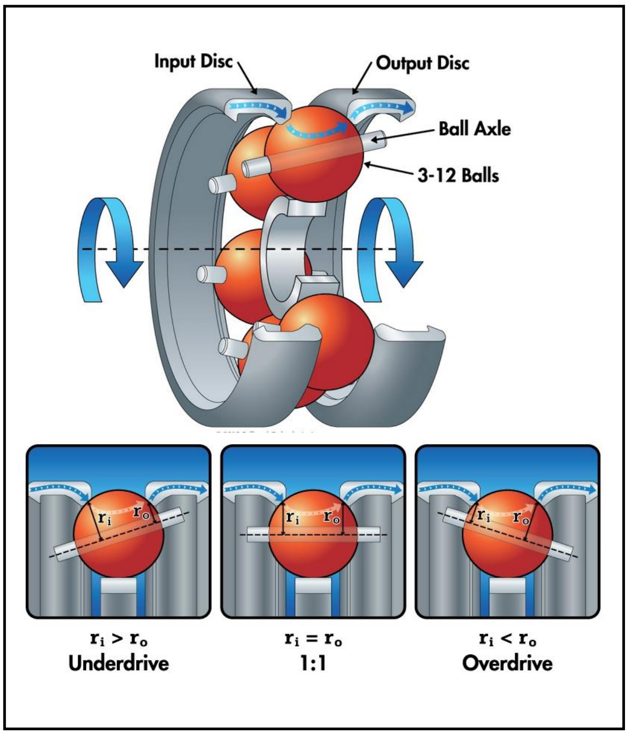


Fig. 3.12: NuVinci [http://www.lockheedmartin.com/us/products/exoskeleton/hulc.html]

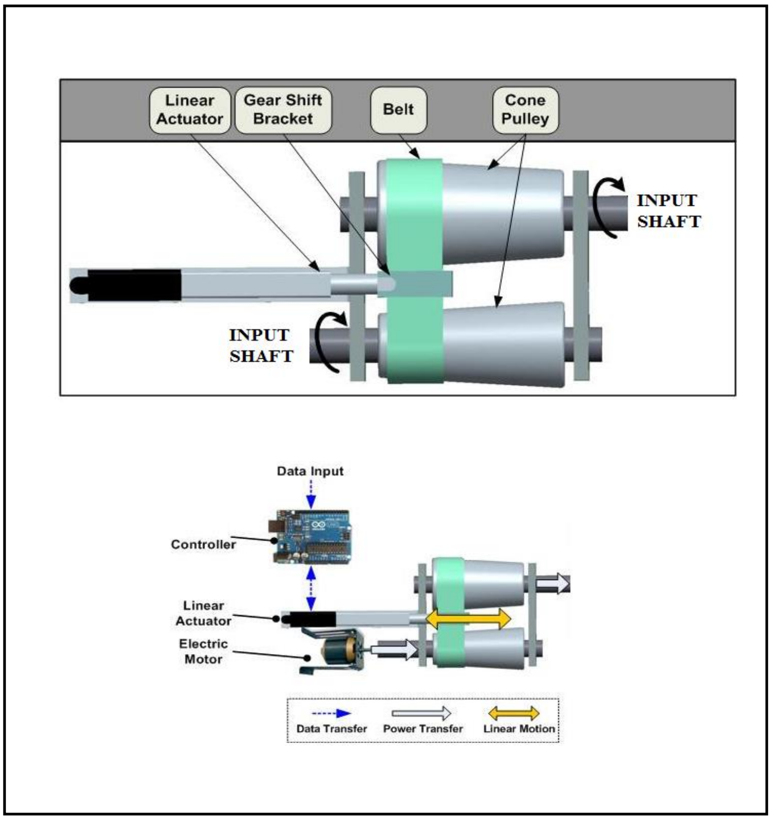


Fig. 3.13: Cone CVT [http://www.smh.com.au/technology/technology-news/iron-man-suit-turns-shipyard-workers-into-super-men-20140805-100n0l.html]

3.4.4 Others

There are many other types of CVTs, which are not commercial yet or are still in research stage. Cone CVT is also a CVT which is not very popular. The schematic diagram of cone CVT is shown in Fig. 3.13, which clearly explains its principle. The change in lever position changes the gear ratio.

3.5 Summary

Table 3.2 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 [56] to obtain infinite speed ratios.

Table 3.2: Comparison of different CVTs

CVT Type	**Speed Ratio Range**	**Observations**
Belt CVT [57]	*0.5-2*	• Small speed ratio range • Difficult to miniaturize
Toroidal CVT [58]	*0.5-2.5*	• Complex torus and roller design • Difficult control strategy
Spherical CVT [59]	*0.2-3*	• Problem of slippage • Traction fluid needed
Cone CVT [56]	*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 in next chapter.

Chapter 4

Modeling and Simulation of a Hybrid Mechanism

4.1 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. Most of them use electric actuators like DC motors to give motion to the wearers' joints e.g. in HAL 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 address 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 discussed in Chapter 3 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.

4.2 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. Mainly gait is divided into two parts: *stance* and *swing* phase, as shown in Fig. 4.1 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.

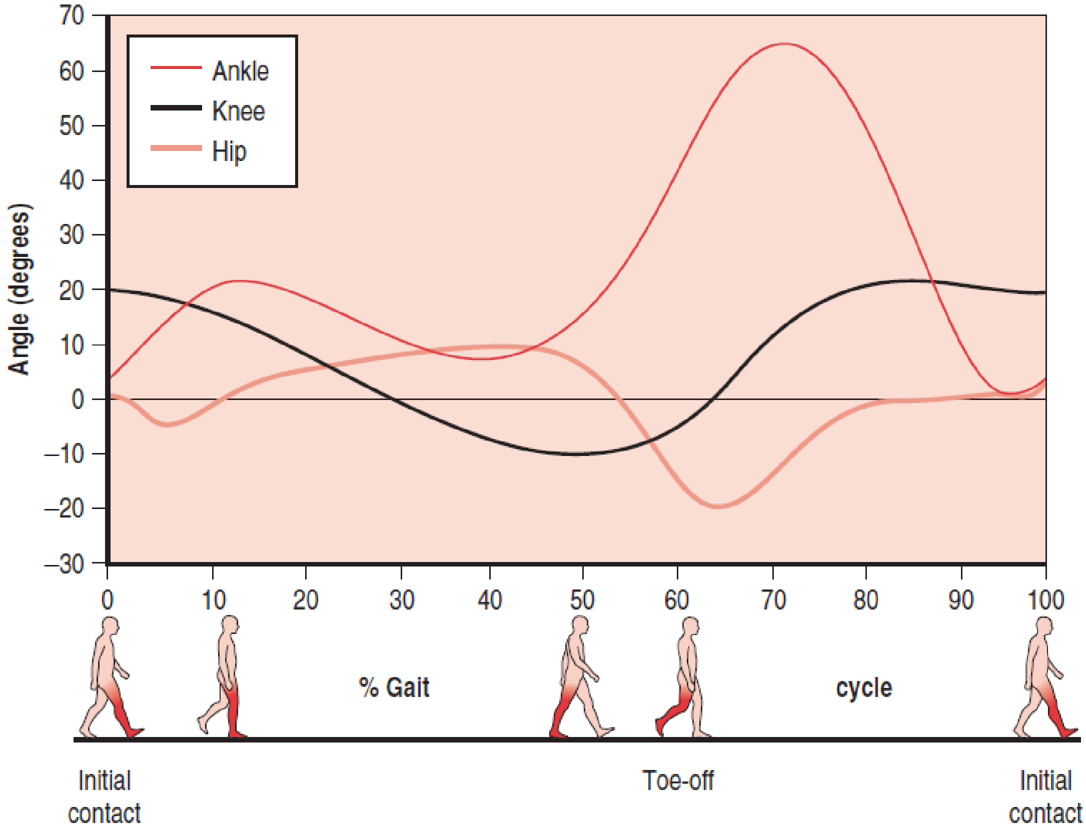


Fig. 4.1 Gait cycle of average human being [Kirtley, 2005]

4.2.1 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

4.2.2 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*.

4.3 Hybrid Mechanism

As the concept of CVT is discussed in the Chapter 3, 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 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.

Scotch Yoke Mechanism

Scotch Yoke mechanisms are defined as conversion mechanisms for translating continuous rotary motion into reciprocating linear motion. These mechanisms find application in internal combustion and steam engines. This shows a similarity with a crank and slider mechanism, only difference being in pattern and range of output which is higher in Scotch Yoke mechanisms and it is capable to transmit high torque because of which it have been taken into consideration in this work. Fig. 4.1 shows this mechanism and initially the slider is at the right position. The rotation of the crank takes place in anti-clockwise direction which results in change in position of slider to the right direction. The range of motion of this mechanism is terminated after a complete rotation of 180 degrees, after which the slider reaches towards the right direction. This reciprocating motion continues as long as the crank continues to turn. The crank being rotating at a constant velocity, the slider attains the value for maximum velocity at boundary conditions i.e., at initial position and final position of the crank. 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.

Four-Bar Mechanism

A four-bar mechanism 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. 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. 4.2 and is inspired from the design of Pons et al.

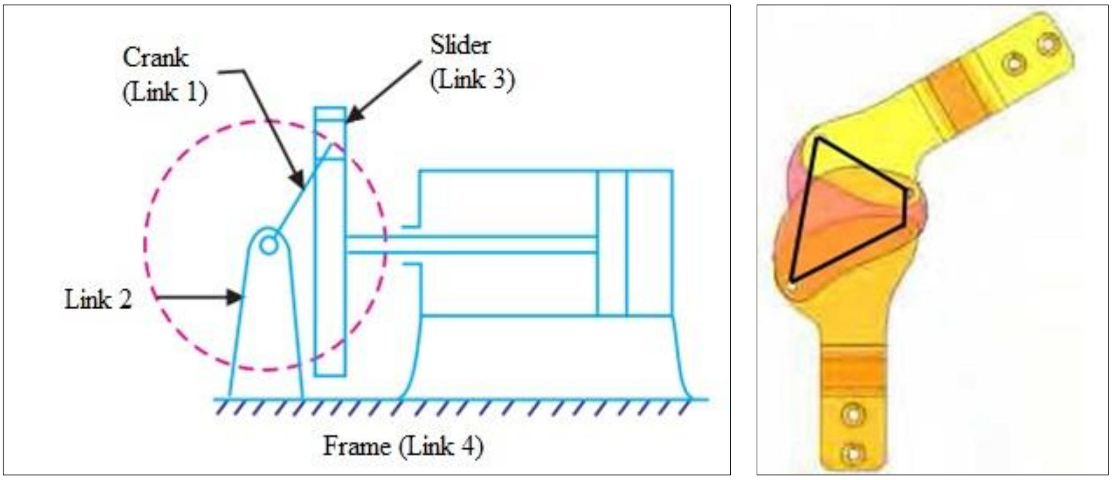


Fig. 4.2: Scotch Yoke and Four Bar Mechanism [J.L. Pons, 2007]

4.4 Mathematical Modeling 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 is shown in Fig. 4.3.

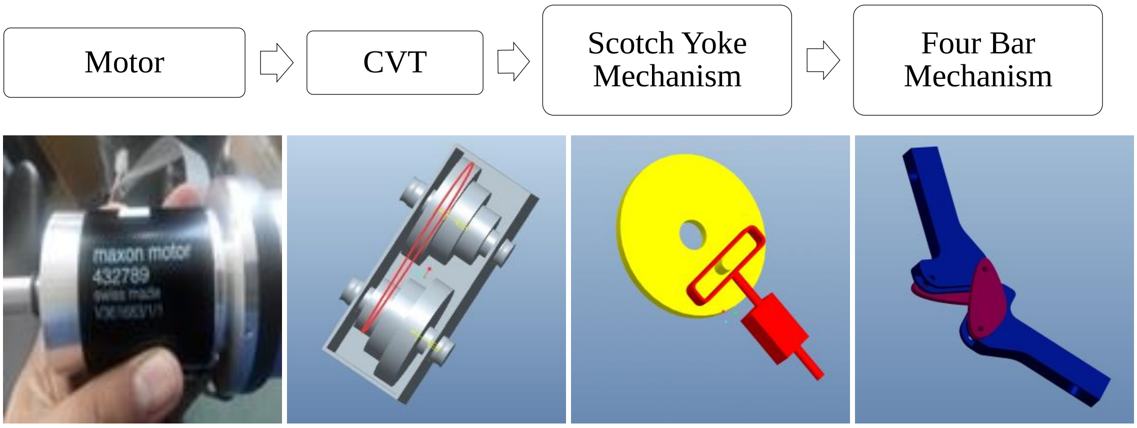


Fig. 4.3: System Flowchart

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.

$$\frac{\tau}{\tau_{sci}} = \frac{d_{i'}}{d_i} \tag{4.1}$$

The amplification of the torque exerted on the crank of the Scotch Yoke mechanism by the motor results due to the geometry of the Scotch Yoke mechanism. The dynamic angle resulting from the rotation of the wheel is also responsible for this. The relation between input and output torque of a Scotch Yoke is given below and is derived from work of Clausen.

$$\tau_{fbi} = \frac{c}{p\sin(\theta_w)}\eta \times \tau_{sci} \tag{4.2}$$

where τ_{sci} is the applied torque provided by the CVT to the Scotch Yoke, 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, the equation of motion of mechanism is derived as follows. The complete solution in terms of input and loading moments is explained by Yildiz *et al*. [71], in which four-bar mechanism is controlled by a CVT and is given as

$$M_{l,r} = M_{in} - N\ddot{\emptyset}_2 - \frac{1}{2}\frac{dN}{d\emptyset_2}\dot{\emptyset}_2 \tag{4.3}$$

After combining (4.1), (4.2), (4.3) and solving by superposition principle, (4.4) can be written as:

$$M_{l,r} = \left(\frac{d_i\tau}{d_i{}'} \times \frac{c}{psin(\theta_w)}\eta\right) - N\ddot{\emptyset}_2 - \frac{1}{2}\frac{dN}{d\emptyset_2}\dot{\emptyset}_2 \tag{4.4}$$

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 percentage in MATLAB environment. The plots are shown in Fig. 4.4 and Fig. 4.5 respectively.

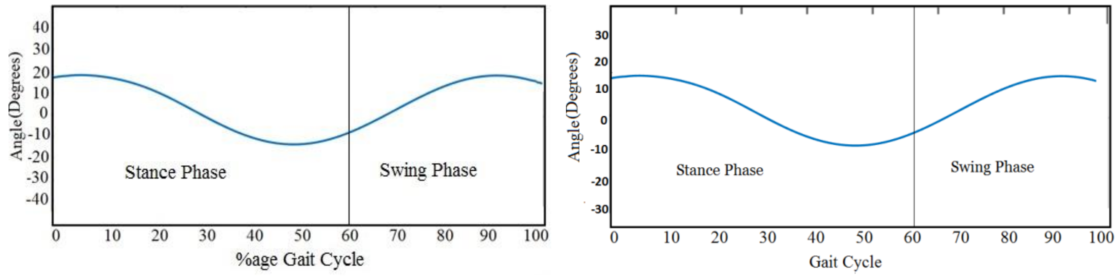


Fig.4.4: Position vs. % gait cycle (Analytical) for 50% and 25% assistance respectively

The plot in Fig. 4.4 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. 4.5, it is seen that initially there is an overshoot peak during the stance phase in almost no time due to the geometrical parameters of scotch Yoke which will be optimized after experimental study 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.

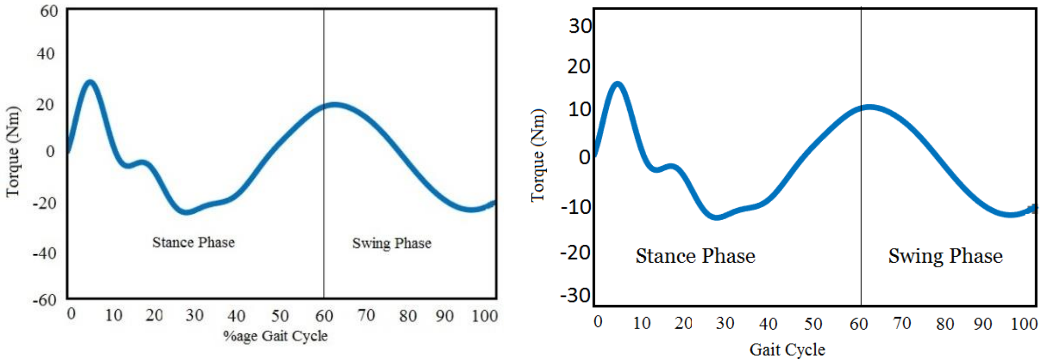


Fig.4.5: Torque Vs. % gait cycle (Analytical) for 50% and 25% assistance respectively

4.5 Geometric Modeling 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. 4.6 and then imported to MATLAB environment for simulation to obtain plots of position and torque exerted. Pro-E Wildfire 5.0 version was used to model the parts and complete assembly.

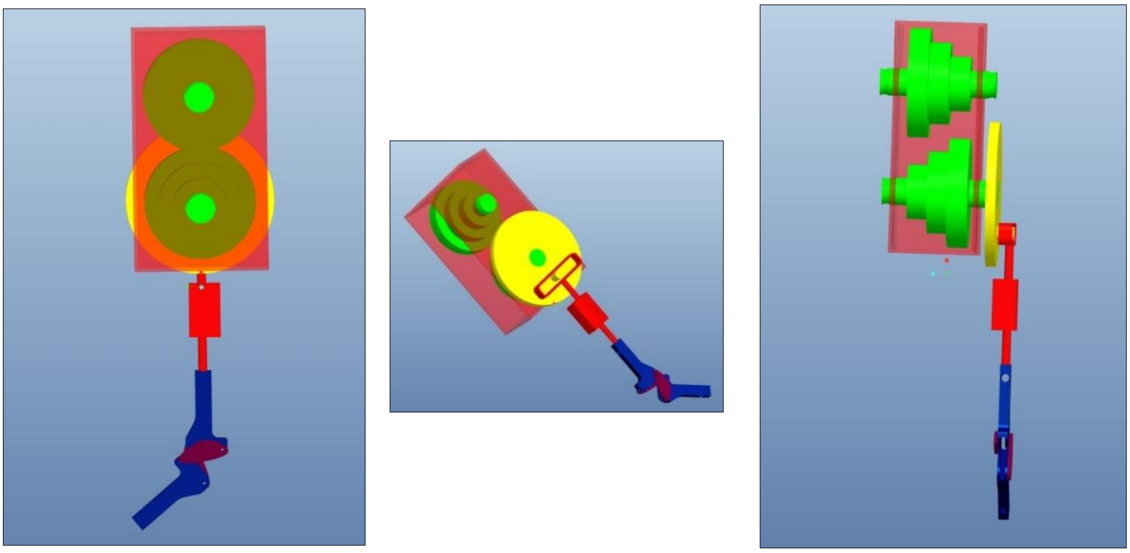


Fig. 4.6: Different views of parts and assembly in Pro-E

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 modeling and assembled with proper constraints, so it 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.

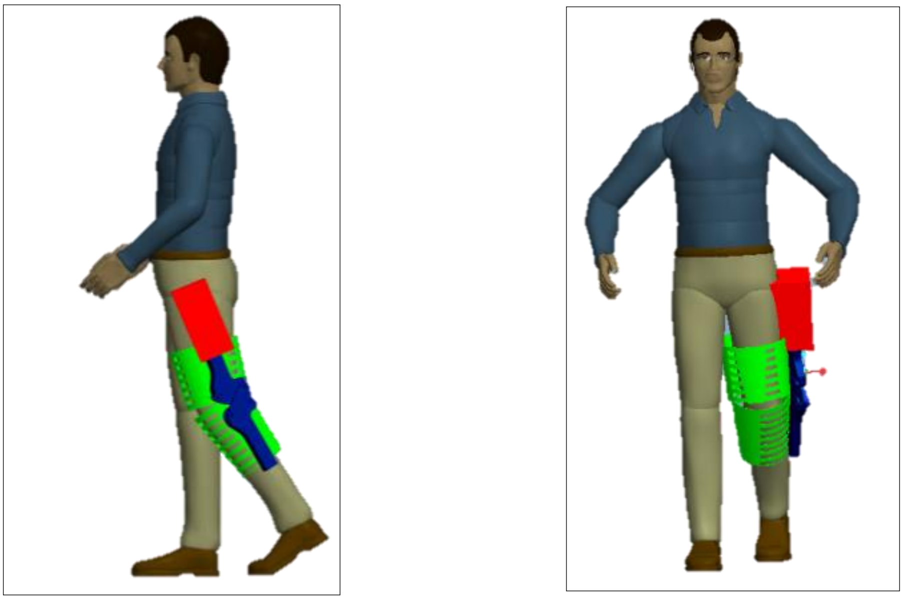


Fig. 4.7: Assembly installed on human body, showing knee joint

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. 4.7, to see the feasibility of design and also to obtain the simulation videos for the integration of our design with human walking. The weight of the complete assembly for one leg, as checked in Pro-E is *16 Kgs.* For initial calculation, material used for the complete device is Aluminum alloy (Al-7075), whose properties are stated in Table 4.1.

Table 4.1: Material Property Table

Material	Property	Value	Units
Aluminum Alloy (Al – 7075)	Mass density	2810	kg/m^3
	Yield Strength	503	Mpa
	Ultimate tensile strength	572	Mpa
	Young's modulus of elasticity	71.7 Gpa	Gpa

For simulation, the final CAD model is exported from Pro-E i.e., its design workplace to Simulink software. For this purpose the .xml file was created which is later imported by Simulink software with the 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. 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.

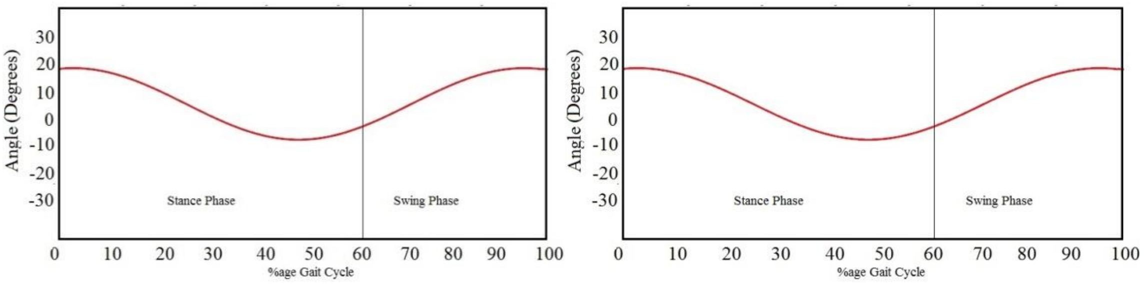


Fig. 4.8: Position vs. % gait cycle (Simulation) for 50% and 25% assistance respectively

Now the plots of the angle and torque were obtained from Simulink Environment and are shown in Fig 4.8 and 4.9 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 are obtained from Simulink interface, where it can be clearly seen that the range of motion comes out to be 60^o [20^o to 0^o, 0^o to -10^o, -10^o to 0^o and 0^o to 20^o] maximum peak angle being 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. 4.9 gives a depiction of torque vs. gait cycle plotted from simulation of the assembly of the complete mechanism.

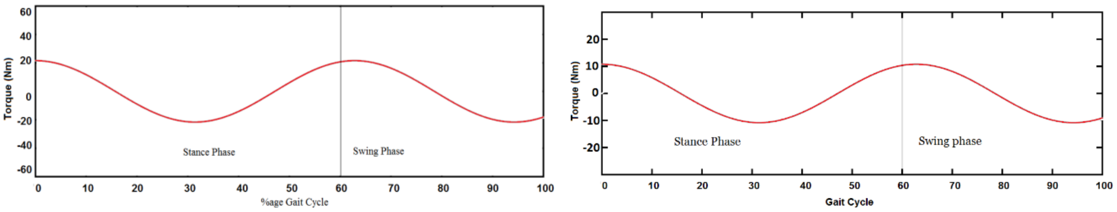


Fig. 4.9: Torque vs. % gait cycle (Simulation) for 50% and 25% assistance respectively

4.6 Simulation Results and Validation

In this section, validation is carried out where both the results obtained from mathematical modelling and geometrical modelling is 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. 4.10 and 4.11 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 [73]. In first case as depicted by Fig. 4.10, 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 work is as effective 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 the second case, in order to verify the torque variations, the results are compared with the normal human walking torque data as shown in Fig. 4.11.

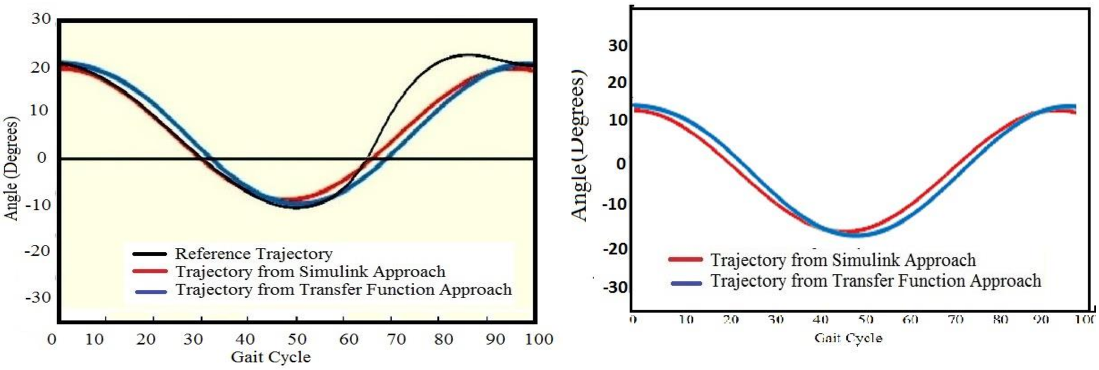


Fig. 4.10: Position vs. gait cycle validation for 50% and 25% assistance respectively

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 20 Nm. This work shows only two speed ratios (50% and 25% assistance) of CVT at initial level which has been verified for different ratios also. The angular speed of crank varies with due effect of different ratios of CVT which is understood by repeating the simulation over physically possible range of ratios of CVT. Therefore results of simulation show that using a CVT that helps in obtaining variable input speed can be used in conjunction with Scotch Yoke mechanism and a four-bar linkage and this setup is feasible under all circumstances.

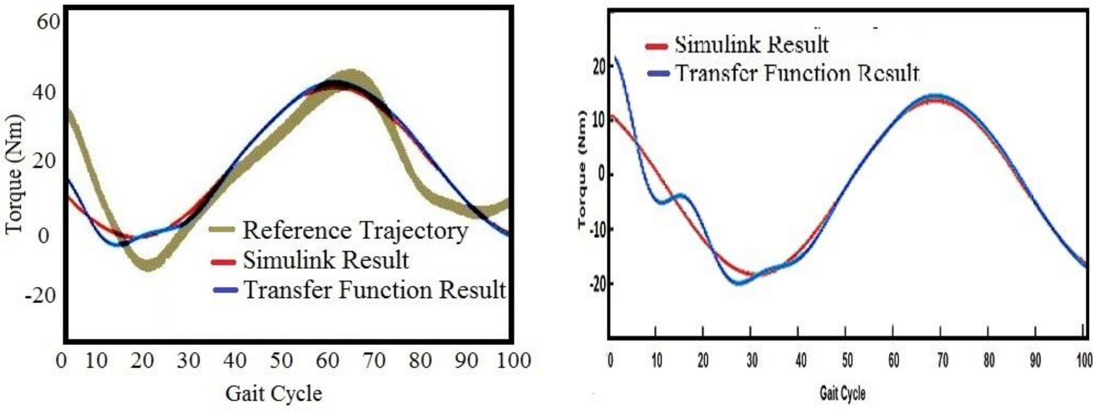


Fig. 4.11: Torque vs. gait cycle validation for 50% and 25% assistance respectively

4.7 Summary

Today in the fast pace environment there is a need for flexible and economical solution for human knee problems due to arthritis and low calcium level that hampers the normal ability to walk. Exoskeleton is the best solution but it is costly due to the use of controllers for controlling the gait cycle. A novel concept of a four-bar mechanism and Scotch Yoke mechanism equipped with a CVT has been proposed to obtain variance in input speeds. In this chapter the use of CVT is discussed instead of controllers to maintain the gait cycle that makes it economical but it would result in the secondary problem i.e. weight. To overcome the situation, the hybrid mechanism was designed based on average human gait cycle by optimizing the weight of mechanical components in feasible region. The dynamics is solved in Simulink and the results obtained are in accordance with the normal human walking gait cycle. The results show that it is optimal to use CVT in place of controllers in the knee joint of exoskeletons along with mechanical mechanisms that would directly affect the cost and decrease complexity of the system. In an ongoing work, the more optimal control with further reduction weight of system is being studied where improvement in design could lead to control of flexion and extension angle in more accurate and efficient way. Moreover, the choice of materials can also be looked upon to reduce the weight but at the same time which could bear the forces exerted and based on application which could take load of a human being in performing full range of motions.

Chapter 5

Design Optimization

5.1 Introduction

As the concept of hybrid mechanism is discussed in the Chapter 4, this chapter explains how further improvement in that design can be done in order to reduce weight of exoskeleton to be wore by the user and also the control strategy for the same. Alike the combination of different mechanisms – Scotch Yoke and four-bar, this section also uses same set of combinations only difference being that hybrid mechanism for both legs can be controlled by single CVT mounted on lower back of the user. Complete approach for the same along with detail design is explained below.

5.2 Improvement in Design

The previous mechanism was designed such that it has to be installed on each leg separately, i.e. two separate CVTs. This makes the total weight of exoskeleton high as each leg has to carry 16 kg of weight. In order to improve this, design modification is proposed. In this a single CVT is used to actuate the mechanism for both legs as shown in Fig. 5.1. First of all, the knee joint is modeled according to specifications from biomechanics [74]. After this geometric model of conical CVT is prepared and assembled with knee joint mechanisms which includes both four bar and Scotch Yoke mechanisms. For maintaining speed ratio, belt drive is used that connects two steps of different wheels of CVT. Both output shafts are attached to Scotch Yoke mechanism of both legs. As this work is confined to only walking, therefore upper bars of mechanism are kept as fixed links, alike in human walking, thigh joint is fixed is sagittal plane.

The main challenge in designing this hybrid mechanism is to maintain a constant phase angle between both legs of user. Moreover this lag should be fine-tuned with changing speed ratio. For this purpose, a proper feedback channel and use of adequate signal waves are used. After this the final simulation is carried out which gives results of angle and torque as desired. For initial calculation, material used for the complete device is Aluminum alloy (Al-7075).

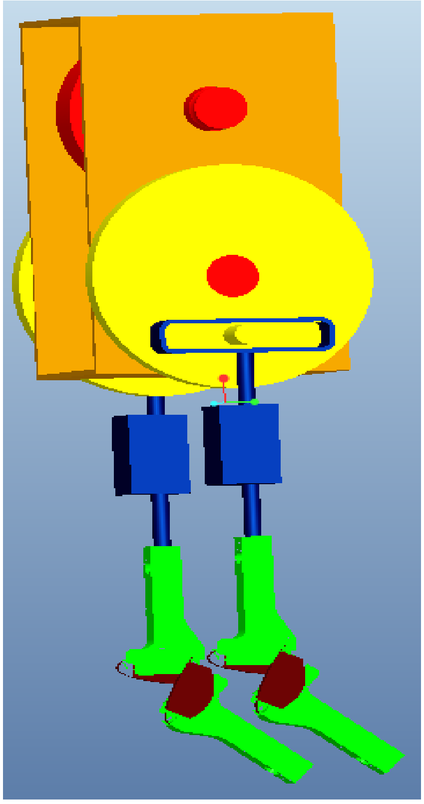


Fig. 5.1: Modified assembly in Pro-E

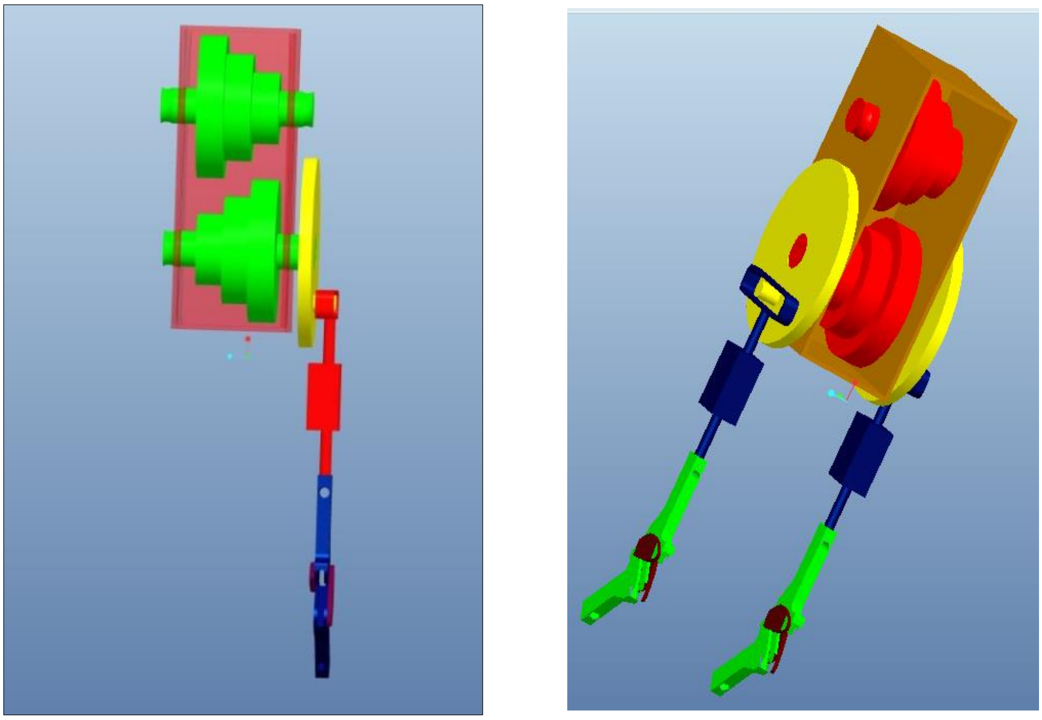


Fig.5.2: Comparison of single leg and two leg CVT

The difference in basic design of single leg and two leg CVT is shown in Fig. 5.2. The weight of the complete assembly for complete model, as checked in Pro-E is *26 kgs* which is less as compared to single leg model in Chapter 4.

5.3 Simulation Results

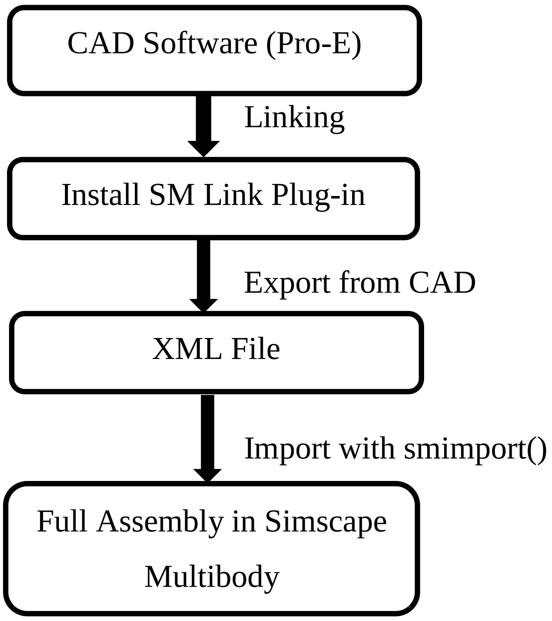


Fig. 5.3: Flow Chart to import design in Simulink

For simulation, the final CAD model is exported from Pro-E i.e., its design workplace to Simulink software, as shown in Fig. 5.3. For this purpose the .xml file was created which is later imported by Simulink software with the 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. 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.

After this plots of position and torque are obtained from Simulink environment in a similar way as stated in previous chapter. In Fig. 5.4-(b), the phase difference can be clearly seen between both knee joints as desired after consequent intervals.

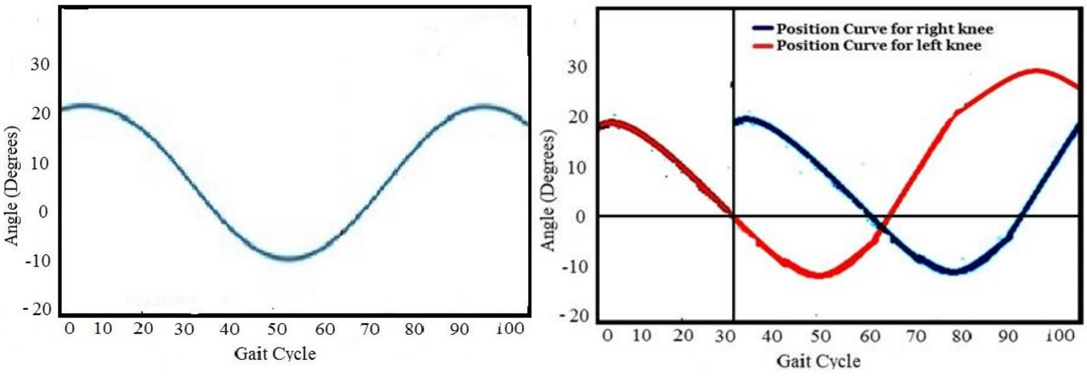


Fig. 5.4: (a) Position vs. % gait cycle (Simulation) and (b) Phase difference between legs

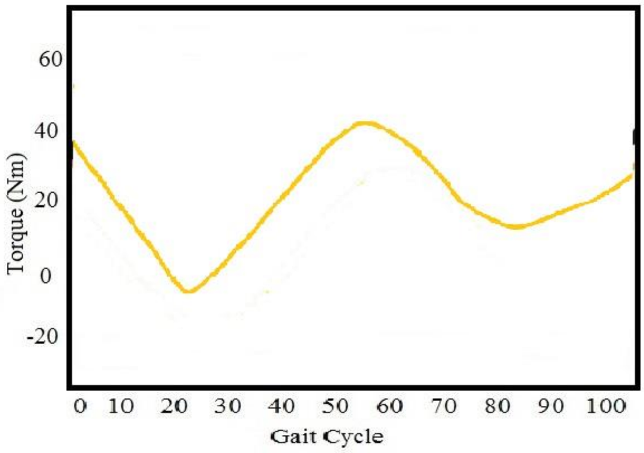


Fig. 5.5: Torque vs. % gait cycle (Simulation)

5.4 Kinect Sensor Results

Kinect is a line of motion sensing input devices by Microsoft for Xbox 360 and Xbox One video game consoles and Microsoft Windows PCs. Based around a webcam-style add-on peripheral, it enables users to control and interact with their console/computer without the need for a game controller, through a natural user interface using gestures and spoken commands. The **Kinect sensor** as shown in Fig. 5.6, is a horizontal bar connected to a small base with a motorized pivot and is designed to be positioned lengthwise above or below the video display. The device features an "RGB camera, depth sensor and multi-array microphone running proprietary software", which provide full-body 3D motion capture, facial recognition and voice recognition capabilities.

Fig. 5.6 : KINECT Sensor

The necessary prerequisites are installed to interlink MATLAB with KINECT. Fig. 5.7 (a) shows the skeleton tracking of human joints, further from which only knee joint is selected to be tracked for path detection. Run the program 'Kinect Tracking' and all the coordinates of the knee joint will be stored in a matrix 'M'. Vary 'n' to change the time of recording. Using this ‘M’ matrix, plot for angle is traced which is covered by human knee as shown in Fig. 5.7 (b).

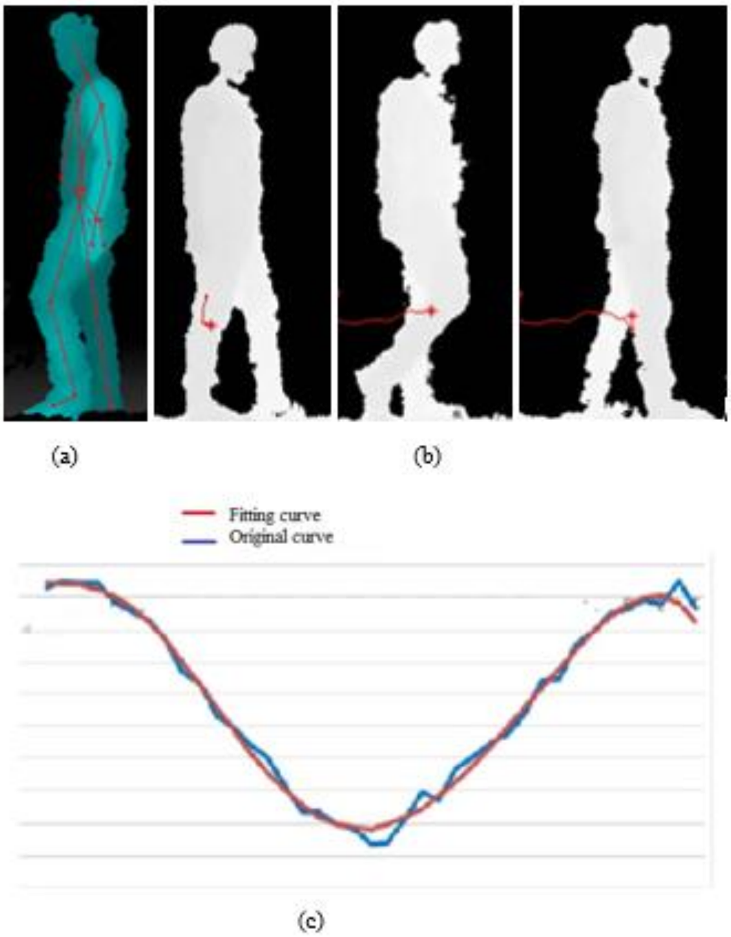


Fig. 5.7: (a) Skeleton tracking through KINECT (b) Knee joint path tracking through KINECT (c) Curve fitting

After the curve is traced for knee joint of one complete gait cycle, as shown in Fig. 5.7 (c), smoothening is done to fit the curve. Final curve for position is shown in Fig. 5.8 which is further validated against results obtained from Simulink and biomechanics data.

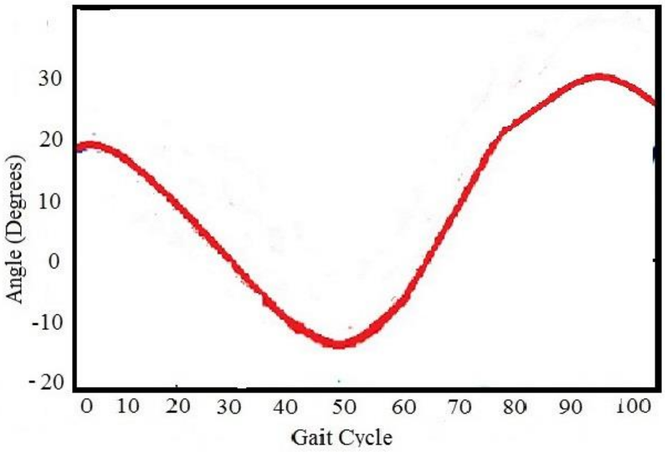


Fig. 5.8 : Position vs. % gait cycle (KINECT)

5.5 Validation

In this section, validation is carried out where both the results obtained from Simulation and KINECT sensor are compared with the normal biomechanical walking data [74]. This is done by superimposing the graphs obtained by simulation and KINECT with normal gait cycle of a human being as shown in Fig. 5.9. In first case, 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 work is as effective as using costly controllers. The only difference observed was overshoot before completion of one cycle, which shows that proposed hybrid model has slight variation as compared to walking of normal human which could be further improved in future work by trying better strategies and further improvement in design.

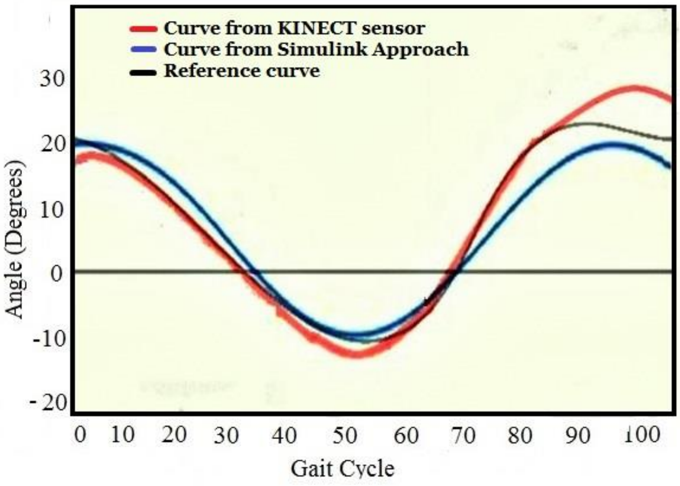


Fig. 5.9: Position vs. % gait cycle (Validation)

In the second case, in order to verify the torque variations, the results are compared with the normal human walking torque data as shown in Fig. 5.10. The torque range for a human being of approximately 70 kg is 36-40 Nm during walking gait cycle at full assistance [73] which is achieved through this design. For this torque range, the simulation results have been obtained using the hybrid mechanism and are found to be almost similar with slight variations at some points which is acceptable for this work at present and could be further improved. Therefore results of simulation show that using a CVT can be used in conjunction with Scotch Yoke mechanism and a four-bar linkage and this setup is feasible under all circumstances.

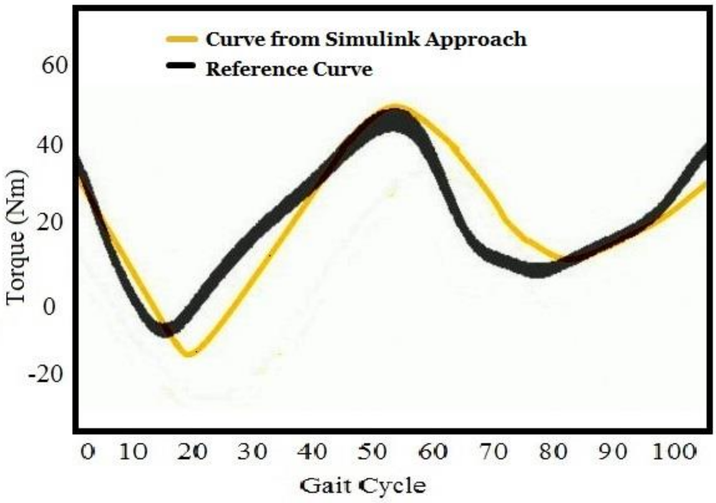


Fig. 5.10: Torque vs. % gait cycle (Validation)

5.5 Summary

In this chapter the use of single CVT is discussed instead of controllers to maintain the gait cycle that makes it economical and also the issue of weight is dealt. To obtain the feasible results, the hybrid mechanism was designed based on average human gait cycle by optimizing the weight of mechanical components in feasible region. The dynamics is solved in Simulink and the results obtained are in accordance with the normal human walking gait cycle. These results are further validated by recording observations from KINECT sensor which helps in tracing path of knee joint during human walking cycle. The final results show that it is optimal to use CVT in place of controllers in the knee joint of exoskeletons along with mechanical mechanisms that would directly affect the cost and decrease complexity of the system. In future work, the choice of material could result in further weight reduction and improvement in design could lead to remove variations observed in this work. In Table 5.1, a comparison between single leg and two leg CVT model is shown:

Table 5.1: Comparison of two knee exoskeletons

	Single leg CVT model	Two leg CVT model
CVT placement:	Thigh of each leg	Lower back
Exoskeleton weight (kgs)	16+16=32	26
Torque required at knee joint (Nm)	20 - 26	36 - 40

Chapter 6

Conclusions and Future Directions

6.1 Conclusions

The study on lower-limb exoskeletons is carried out which focuses mainly on the design part of the torque variation and motion tracking 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.
- Adding to the research, a hybrid mechanism for each leg 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.

- Adding further, the design has been optimized in which only one CVT was used to control both the legs. This resulted in weight reduction of exoskeleton and achieving torque range for full assistance.
- Moreover, due to change in placement of CVT, the optimized design resulted in better comfort as compared to single leg model.
- Finally, the results from geometric model of the complete mechanism assembly were compared with results obtained from KINECT and validated with the normal walking gait cycle.

6.2 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.
- 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.

6.3 Scope of Future Work

Some new concepts are brainstormed and shared here for the purpose of throwing some light on the future work directions of the author.

6.3.1 Concept 1: Extracting Energy from the User

When thinking of a wearable exoskeleton, a person would usually think of a device that somehow augments or monitors the user. But what if exoskeleton technology was used to extract energy from the person wearing it?

- The prototype is a leg brace with a dynamo strapped on the knee.
- The flexion and extension of the knee spins a motor which charges a capacitor that in turn, charges a battery.
- In the case of exoskeleton systems however, the user is already wearing a complicated piece of equipment and only the functionality of capturing energy would have to be added.

Fig. 6.1: Prototype of concept [Rice University]

Having exoskeletons that can capture and retain energy from the wearer could be very useful in future designs. Example applications could be military exoskeletons that have been damaged or have been used on an abnormally long deployment and the soldier has ran out of battery power for his or her GPS/radio/light. In this case, an exoskeleton or exoskeleton segment that can charge equipment while on the move could prove to be invaluable. Another application could be in resistive exoskeletons, for example an exoskeleton for astronauts that hinders movement to counteract muscle atrophy in space could also generate electricity.

6.3.2 Concept 2: A Continuous Rotary Actuation Mechanism for a Powered Hip Exoskeleton

- A new mechanical design for an exoskeleton actuator to power the sagittal plane motion in the human hip.

- The device uses a DC motor to drive a Scotch Yoke mechanism.
- Both the peak and average motor torque can be reduced.
- Potentially allowing a less powerful motor to be used.
- The motor never needs to reverse direction even when the hip joint does.

Fig. 6.2: Device mounted to side of user [H. Vallery, 2015]

6.3.3 Concept 3: EMG driven Model (Even for Paralyzed)

- EMG controlled exoskeletons are available which are useful only for healthy patients in terms of strength of cells because stroke affected people do not have that much strong cells which can control such exoskeletons.
- Incorporation of new technological innovation named as ‘Stentrode’ could revolutionize this sector. It will be implanted into a blood vessel next to the motor cortex, bypassing the need for complex brain surgery.

- From there it will pick up brain signals and allow patients to move a robotic exoskeleton attached to their limbs simply by thinking about it.
- Conversion of acquired signals into electrical commands will be used to control exoskeleton. The need is to establish system that can capture, decode and pass wireless signals through skin to integrate with exoskeleton.

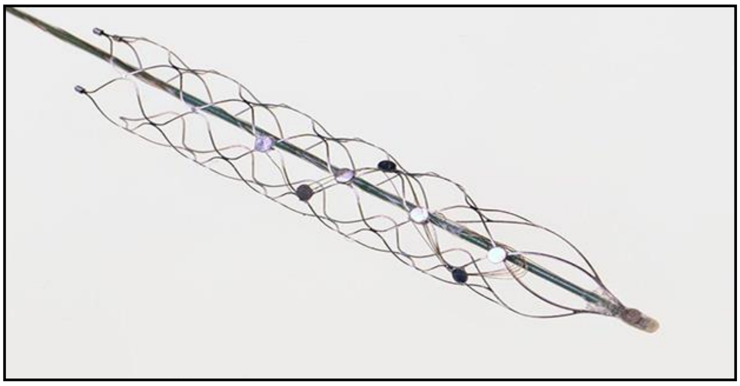


Fig. 6.3 Stentrode [DARPA]

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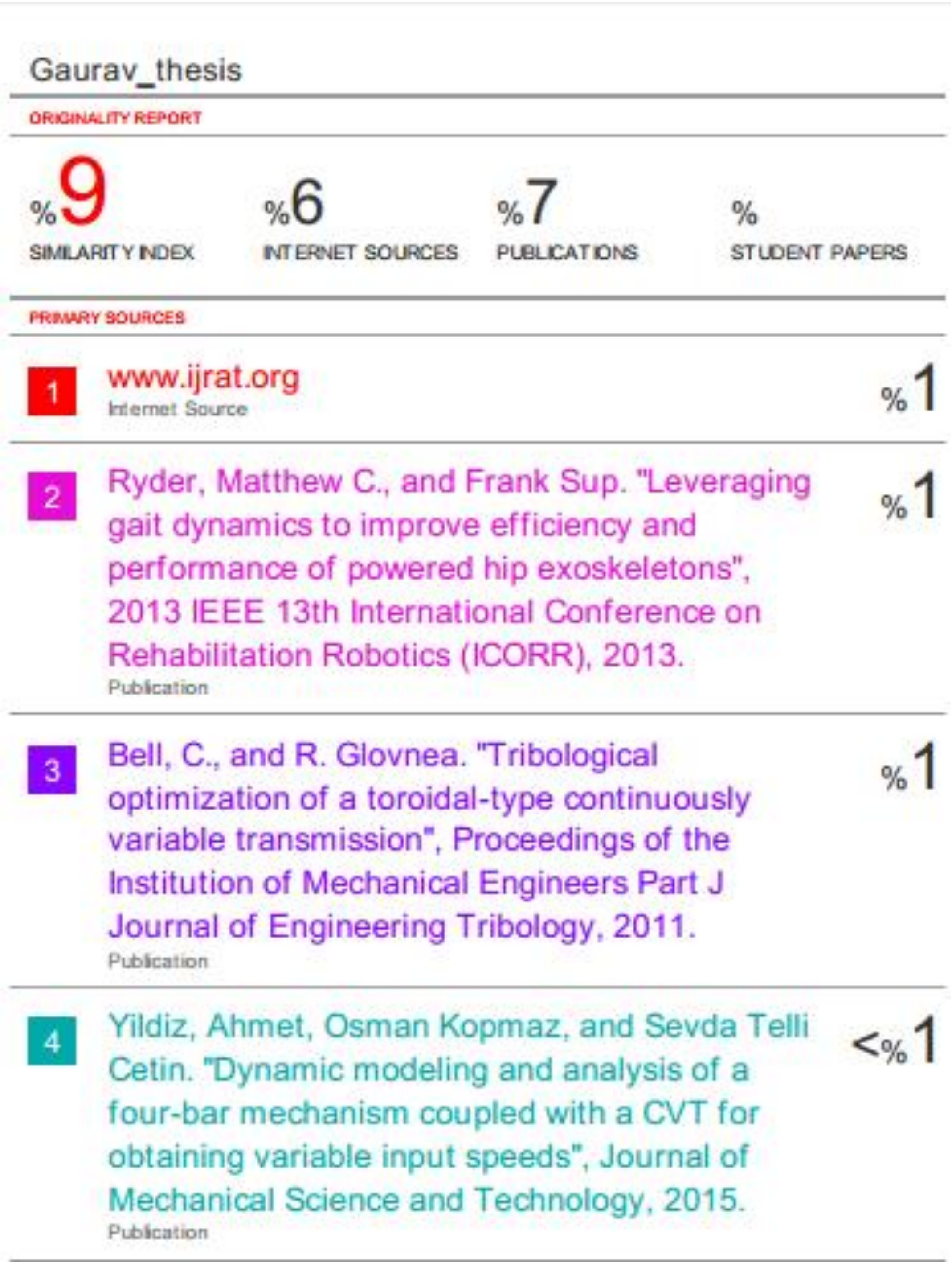

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