UNIVERSITY OF STRATHCLYDE

Wearable Robotics for Rehabilitation

This Thesis is submitted in partial fulfilment of the requirement for the degree of M.Sc. in Bioengineering Unit

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DECLARATION

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I especially like to appreciate my counter strength, my husband and family for being extremely supportive. Their love, encouragement and word of confidence made my journey possible.

ABSTRACT

Robots have become an integral part of modern industrial manufacturing. In healthcare, the impact of robotic devices has not yet been established but there has been considerable discussion on their use as assistive devices and as products or systems that aid in rehabilitation of disabled people. I will technically investigate the current state-of-art wearable robotic devices in relation to physical rehabilitation and use of robots as assistive technology. Assistive technology is defined as use of a device to replace or to substitute function of missing limb of the user, and rehabilitation technology is the robotic device that should improve the individual's recovery of function.

Wearable robots are generally electro-mechanical devices that are fitted to the user to facilitate rehabilitation or to allow the user to retrieve a lost or diminished capacity for purposeful movement. Wearable robots can be used either as an orthotic device; in case of dysfunction of limbs or as a prosthetic device that compensates for missing limbs following amputation. The challenges for the breakthrough of robotics into modern healthcare will be related to providing superior user interaction, ease of use and training and above all better functional outcome over that achievable by conventional rehabilitation methods or non-robotic assistive technologies.

The project will review current commercial and disclosed research devices associated with upper limb and lower limb function. The field will be divided into functional categories related to reaching and grasping and standing and walking in exoskeleton and prosthetic devices. A key aspect of the review will focus on the mechanics and control approaches used to allow the user to train within a robotic system or control it to perform a task. The report will also critically look at solutions offered in relation to wearability, comfort and safety of use and the intended patient groups. Examples of the type of devices that will be included in the report are recent exoskeletons such as ReWalk from Argo Medical Technology, wearable walking robots such as KineAssist, MoonWalker as well as the more established body weight support treadmill training devices such as the Lokomat by Hocoma.

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LIST OF ABBREVIATIONS

AAN	Assistance As Needed
ADL	Activities for Daily Living
AFO	Ankle Foot Orthosis
ALEX	Active Leg Exoskeleton
ALEX	Active Leg Exoskeleton
ARTHuR	Ambulation Assisting Robotic Tool for Human Rehabilitation
BCI	Brain Computer Interface
BLEEX	Berekeley Lower Extremity
BWS	Body Weight Support Training
BWS	Body Weight Support
CLEMS	Closed Loop Electric Muscle Stimulation
CLME	Complimentary Limb Motion Estimation
CPG	Central Pattern General
DAPRA	Deference Advanced Research Project Agency
DCS	Distributed Control System
DOF	Degree of Freedom
DRNN	Dynamic Recurrent Neural Network
DSA	Digital Servo Amplifier
ECG	Electrocardiogram
EHPS	Exoskeleton for Human Performance Augmentation
EMG	Electromyography
FAC	Functional Ambulation Category
FDA	Food and Drug Administration
FEM	Finite Element Method
FES	Functional Electric Stimulation
HAL	Hybrid Assistive Limb
HB	Human Body

HEPU	Hydraulic Electrics Power Unit
HMI	Human Machine Interface
IMU	Inertial Motion Unit
LCD	Liquid Crystal Display
LLRR	Lower Limb Rehabilitation Robot
LOPES	Lower Extremity Power Exoskeleton
PAM	Pelvis Assist Manipulator
PC	Personal Computer
POGO	Pneumatically Operated Gait Orthosis
PWS	Partial Body Weight Support
RAGT	Robotic Assisted Gait Training
ROM	Range Of Motion
SAS	Stroke Activity Scale
SCI	Spinal Cord Injured
SEA	Series Elastic Actuators
VMC	Virtual Model Control
VR	Virtual Reality
VRTE	Virtual Reality Training Environment
WISCI	Walking Index for Spinal Cord Injury
WR	Wearable Robot
ZMP	Zero Moment Point

CHAPTER 1: INTRODUCTION

Concept of wearable robotics appeared when industrial robotics was modified to create humanoid robots. Person oriented robots that can be worn by users emerged and offer new hopes for assisting those with chronic disabilities and conditions. Conceptually, wearable robotic devices can provide the motive power and function to human paretic limbs bringing them into a class of devices that move from passive orthotic/ prosthetic devices to ones which actively move the body in purposeful ways.

Though there are potentially a number of users worldwide and some systems are commercially available. It is the future demand that will come with ageing populations that will be the biggest stimulus to growth in this sector.

Lower birth rates and advancement in medical technologies and health care are contributing in the aging population. In countries like china, population control policies are creating a serious shortfall between young and ageing population, which ultimately affecting to the national economy due to lack of working aged population. In such a situation, use of wearable robotics can replace a missing limb or can be used as a rehabilitative device to cure disabilities. As a result, population with missing limbs or disabilities may also experience a quality life with contributing in progress of society.

Michael Hillman stated that, during 1950s, only 4.9% of the population of the world was over age of 65. Currently, this has raised to20% .In 2050, it may go beyond 35% [1]. Additionally war records show that during world war second, 30% of injured combatants died. With improved battlefield medicine the number of injured service men dying of their injuries has fallen to 6% but the number with amputation or need of personal assistance has risen. Increasing average age of death and decreased death toll has created a vast demand on rehabilitation and assistance. Robotics can be turned out as an effective solution by providing wearable suits as an exoskeleton to replace lost limbs or as a device providing visual, communication or hearing aid to the person.

1.1 WEARABLE ROBOTICS TECHNOLOGY

Wearable robotics is substantially dependent on sensors and actuators technology. Sensors are crucial to maintain communication between user and robot. Information obtained from sensors is processed by control system that actuates desired joints of robot through actuators.

At a first glance, WR can be classified with the function they perform in cooperation with the user. Classification: Empowering robotic exoskeleton, orthotic robots and prosthetic robots.

Empowering robotic exoskeleton: Originally called Extenders, were devices that extended strength of human arm beyond its natural limit. This exoskeleton was dependent on the mapping of human anatomy. User, who wore it, could control this device. Master-slave configuration was used.

Orthotic robotics: Subject uses this mechanical structure to regain lost or weak functions of limb following neurological disorders. Device maps the human anatomy and interaction between user and machine drives device to produce an appropriate power output in order to provide rehabilitation.

Prosthetic Devices: These electromechanical devices replace or substitute lost limb following an amputation. Use of intelligent robotics technology and human machine interface enable the device to provide human functions as natural as possible to substitute the lost limb function.

1.2 IMPORTANT DEFINITIONS

Robot: “A reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks” [1].

Rehabilitation: “The restoration of the person to an optimal level of physical, mental, and social function and wellbeing” [1].

Physical human-robot interaction: “pHRI is the generation of supplementary forces to empower and overcome human physical limits, that might be natural or result of disease or trauma” [2].

Cognitive human-robot interaction: “cHRI generates the human awareness of the possibilities of the robot while allowing human to maintain control of the robot at all the time” [2].

1.3 HISTORY

History of the rehabilitation can be traced back to thousand years. Concept of using robotics for rehabilitation emerged in early 1960s when CASE manipulator with 4 DOF was proposed to move the patient’s paralysed arm [3] [4]. Rancho Los Amigos *Golden Arm* manipulator with 7 DOF was another powered orthosis presented in early 1970s [3] [4]. This work was the milestone of the technology as it was a time when concept of integrated circuit was just introduced; a decade before microprocessors and size of computers was in the process of reduction [3] [4].

In 1960s, Cornell University in cooperation with General Electric Research received funding from U.S. office of Naval Research to develop full body exoskeleton. This ‘Hardiman’ project focused on increasing strength of the user. Despite some satisfactory results, researchers failed to clear obstacle of lower limb components [5]. Concept of full body exoskeleton, inspired from ‘Pitman’ was proposed in mid-1980s in order to increase the physical strength of soldier; however concerns regarding power supply and implementation remained unanswered [5].

During 1980s, Hok Kwee started project MANUS; first wheelchair mounted manipulation robot for upper limb who provided task specific training with visual feedback to the paretic arm [3]. Jacobsen developed computer controlled upper arm prosthesis named ‘Utah/MIT artificial arm’ and ‘Dextrous hand’. Southampton University started long term project; Southampton Hand later continued in Oxford by Nuffield Orthopaedic centre. This complex five fingered hand project was continued later in Edinburgh as the ToMPAW project.

Palo Alto invented MIME system for upper limb rehabilitation that can be used on bilateral mode, passive or active; supporting user’s affected as well as unaffected limb. GENTLE/S project proposed upper limb rehabilitation for stroke patients [4]. Similar to MIT-manus project, this device motivated user to move hand against a resisted haptic arm on the computer screen [4].

In 1990s, DAPRA and European Commission financially supported and encouraged a number of projects on robotics; exoskeletons to enhance physical strength of a human as well as to improve rehabilitation sector.

1.4 TAXONOMIES

Classification of robotic devices can be done on the basis of its function or the human body structure such as lower extremity or upper extremity.

Generally robotic devices are categorized as Therapeutic devices (Rehabilitative) or Assistive devices. A rehabilitative device is a controllable intelligent machine which helps patient to perform a task or movement and will include monitors/ screen. Monitors or screen allows changes in the performance of the individual to be monitored throughout the rehabilitation process. Rehabilitative devices provide suitable alternative solution for conventional therapy because of several reasons [1]: 1. After proper set up (speed, time), the automated machine can apply therapy (exercise) of varying intensity [1]. 2. Monitors can keep track of work performance of patient. Sensors can measure a response and adaption from a patient’s body (not yet measurable by clinical scale) and can display/ quantify any motor recovery that may have occurred. System also offers ways to motivate a patient by feeding back the person’s performance in one way or another [1]. 3. Robotic devices should not be thought as a replacement for a therapist team but can support the therapist’s work by providing a means to produce intensive rehabilitation that is not dependent on staff resource alone. This can mean more patients treatment with better outcomes that can be achieved through conventional clinics [1].

Assistive devices can be categorized according to its function such as manipulation, mobility or cognition. Manipulation aids can be further classified as fixed-platform, portable-platform and mobile autonomous types. Fixed-platform robots perform functions on a fixed platform such as desktop, kitchen etc. Portable types are manipulated arms attached to an electric wheelchair to do movements or to interact with the environment. Mobile autonomous robots can be controlled by voice or other means to carry out manipulation. Mobility aids can be divided into electrical wheelchairs with navigation system or mobile robots such as motorized walkers. Mobility robot helps patients to cope with mobility impairment by providing support and stability. Cognitive robotic devices assist patients having physical disorders that affect communication and physical well-being such as autism.

Robotic devices can be divided according to the human body extremities as well; upper extremities (arm, hand therapy or assistive devices such as MIT MANUS, myoelectric hand) and lower extremities (gait rehabilitation or artificial limb such as Lokomat gait trainer, ALEX). Primary aims are to provide rehabilitation or complete assistance to the human body [4]. Functioning of these devices can be based on the end effector control and posture control. The end effector based robotic devices are easy and comfortable for the patient. Users do not feel the strain wearing heavy and bulky devices. However, an end effector based devices are not seriously concerned about posture control of lower or upper extremity. Accordingly, there is risk of joint injury. So this issue must be taken into consideration and fully insured in an operation and safety measures. On the other hand, in posture controlled robotic devices, joint axes are determined so that desired motions of the body, anatomical positions can be achieved safely. Rehabilitative devices for gait rehabilitation are usually bulky, heavy and difficult to transport. Hence, robotic devices can be further divided into two categorize: Indoor and Outdoor. Rehabilitative devices such as treadmill gait trainer, footplate manipulators are usable for indoor training sessions only; while exoskeletons, orthotics, prosthesis are the devices developed for outdoor use. All these devices will be discussed in the further report.

WR devices for lower limb can be further classified according to their construction and working principles.

1. Body weight support treadmill gait trainers
2. Active foot orthosis
3. Wired Robot (cable driven robot)
4. Footplate manipulators
5. Stationary gait trainers
6. Over ground gait trainers
7. Exoskeletons.

For this literature review, we will be categorizing and studying wearable robotic devices according to aforementioned classification.

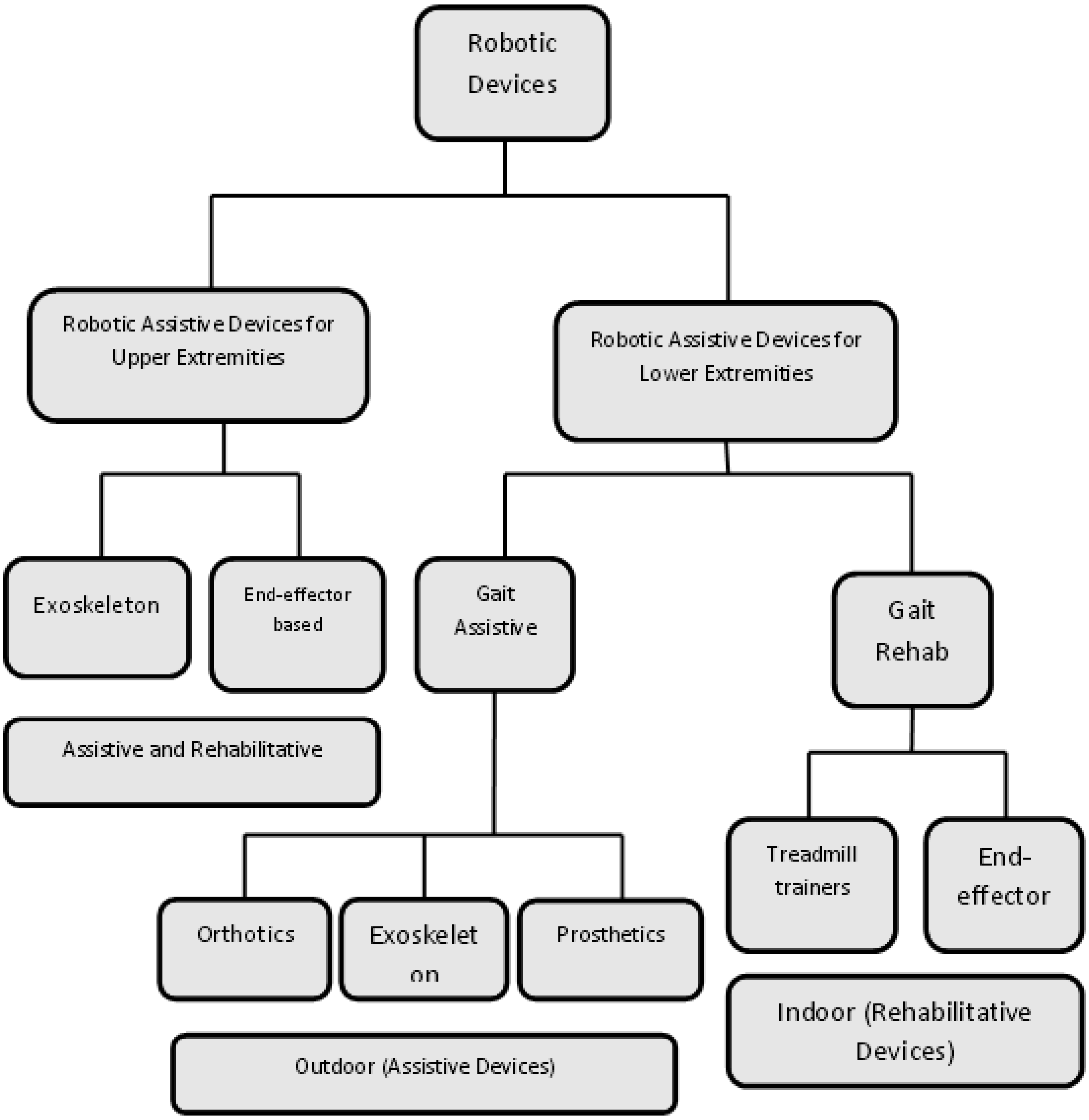


Figure 1.1: General Classification of Wearable Robotics.

1.5 OVERVIEW

There is a developing interest in robotics applications due to a combination of demographic trends resulting in an aging population; and an increased passion for fitness and rehabilitation [2]. Robotics offers a reliable solution for problems of disability victims. It is essential to review robotics technology by analysing an available literature on the development of robotics as rehabilitative or assistive device, current challenges and future areas for research advancement of the further research.

Following neurological disorders, diseases or injuries; an individual becomes unable to interact physically with the immediate environment or to perform his activities of daily living (ADL). The disabled person needs an attendant to assist him in relearning or to help him to achieve p his daily activities where relearning is not possible [1]. In such a situation robotics can provide vital support. Use of assistive or rehabilitative devices can enable him/ her to live independently. Study shows, use of such a devices for children with disabilities in their childhood have shown a positive improvement in their physiological and locomotive behaviour [Butler 1986, [4]]. Robotics rehabilitation and assistive technology are a combination of industrial robot and medical physiotherapy. In this report, we will be focusing on Robotic Devices for Lower Limb Rehabilitation.

Chapter 2:

In this section, we will focus on fundamental terminologies, definitions, motivation behind the use of robotics for rehabilitation, classification, background and technologies related to the rehabilitation robotics. As the rest of the report will be based on the classification, it is essential to specify classification and related technologies. In the report, robotic devices have been compared on the basis of their used technology, construction, control systems and clinical use. All these aspects and expectations for the effective robotic system will be discussed in this chapter.

Chapter 3:

We will evaluate BWS treadmill gait trainers in this chapter. Concept of treadmill gait trainers and body weight support system; its advantages/ disadvantages over conventional physiotherapy will be discussed. Robotic devices based on this principle such as Lokomat, Lopes will be examined for a consideration of construction, control systems, safety management clinical studies and who may benefit from their use.

Chapter 4, 5, 6, 7, and 8:

Active foot orthosis, wired robots (cable driven robot), footplate manipulator robots, stationary gait trainers, over-ground gait trainers and exoskeletons will be reviewed respectively as per the same class of device. All technologies and related benefits and limitations will be discussed. Devices based on these technologies will be reviewed according to construction method, components, control system, safety issues and advantages/ disadvantages. Clinical studies, evaluation experiments will be given to discuss on the feasibility and utility of the device. Further scope for the development will be mentioned in case of few devices.

Chapter 9:

The final section of the thesis will summarise the review. Here the short comings of various devices and limitation of available research findings will be discussed in order to identify how the field is progressing, what obstacles exist in the adoption of robotic devices and what are the key future questions that need to be addressed. This area of work is often poorly reported in the scientific literature due to commercial sensitivity and lack of appropriately conducted trials. Nevertheless, the thesis will aim to provide an overview of the available knowledge base.

CHAPTER 2: METHODOLOGY

In this literature review, ‘Wearable Robotic Devices for Rehabilitation’ were studied. Wearable robotic devices can be categorised upper limb devices, lower limb devices and full body exoskeletons. We decided to study devices available for lower limb devices and full body exoskeletons only, due to the limited scope of the project. Though exoskeletons can be developed only for lower limb or full body, both categories have been considered in this review.

2.1 DATA COLLECTION

Wearable robotic devices and robotic exoskeletons available for lower limb rehabilitation and robotic exoskeletons designed for full body assistance were searched. For this search database explored and found to contain appropriate materials included Wiley online library, *IEEE*, Springer link, ACM and Elsevier Digital Libraries were used. Journals such as International Journal of the physical Sciences, Journal of Rehabilitation Research and Development and Journal of Neuro-Engineering and Rehabilitation were reviewed. Proceeding reports such as; proceedings of World Congress of Intelligent Control and Automation, International Conference on Rehabilitation Robotics, International Conference of Control, Automation and Systems, International Conference on Robotics and Automation were searched to collect information on wearable robotics for rehabilitation.

Information related to clinical studies of devices was searched at the database of clinical trials and information published by SAGE publication on behalf of American Society of Neuro-rehabilitation was used in this review.

All papers, reports, books, webpages were searched with specific words or phrases. Bullion operators such as AND, OR, NOT were used to obtain accurate results. Option of ‘advanced search’ was used some time to reach at desired database.

Besides of these established and reliable sources; websites of manufacturers, newsletters, websites of medical devices, blogs of rehabilitation robotics were also searched in order to obtain information regarding recent developments, market conditions for robotic devices, upcoming technologies, and accurate specifications of devices including costs were considered. For this research, Google and Yahoo search engines were used.

2.2 DATA CLASSIFICATION

Collected data was primarily classified according to WR devices, WR technologies and clinical trials. WR devices were classified further according to their design concept and working principle. WR technologies were reviewed on the grounds of sensors, actuators and control strategies. Data related to clinical trials then utilised to evaluate and compare described robotic devices.

2.3 TIME SPAN OF THE REVIEW

Since middle of the last century, robotics field has emerged as a vast area of on-going research and development. It was not possible to review all devices here. So we decided to stick with a time span of 8 years (2004-2012) and devices those had been developed before 2003 are mentioned in a historical review. In historical review, all kind of rehabilitation robotic devices have been considered.

CHAPTER 3: HUMAN BODY MECHANISM AND GAIT ANALYSIS

3.1 BIO-MECHANICS:

It is essential to study biomechanics of human movements before evaluating technical and clinical aspects of wearable robotic devices. In this chapter, we will review musculoskeletal structure of lower limb, biomechanics and challenges associated with designing of lower-limb exoskeleton.

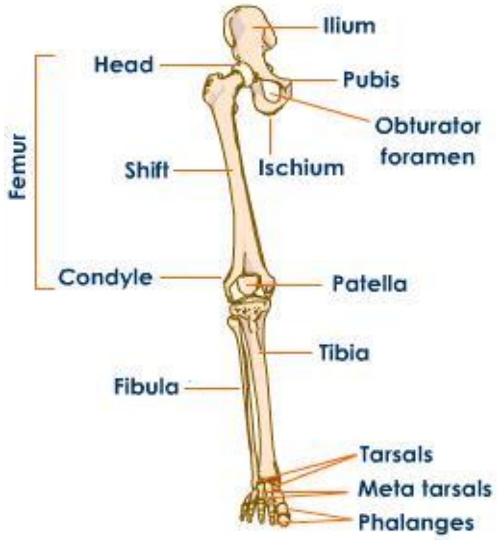


FIGURE 3.1: MUSCULOSKELETOL STRUCTURE OF LOWER LIMB[6]

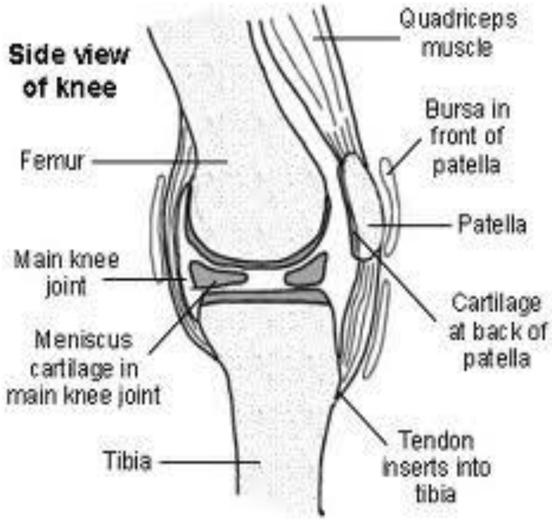
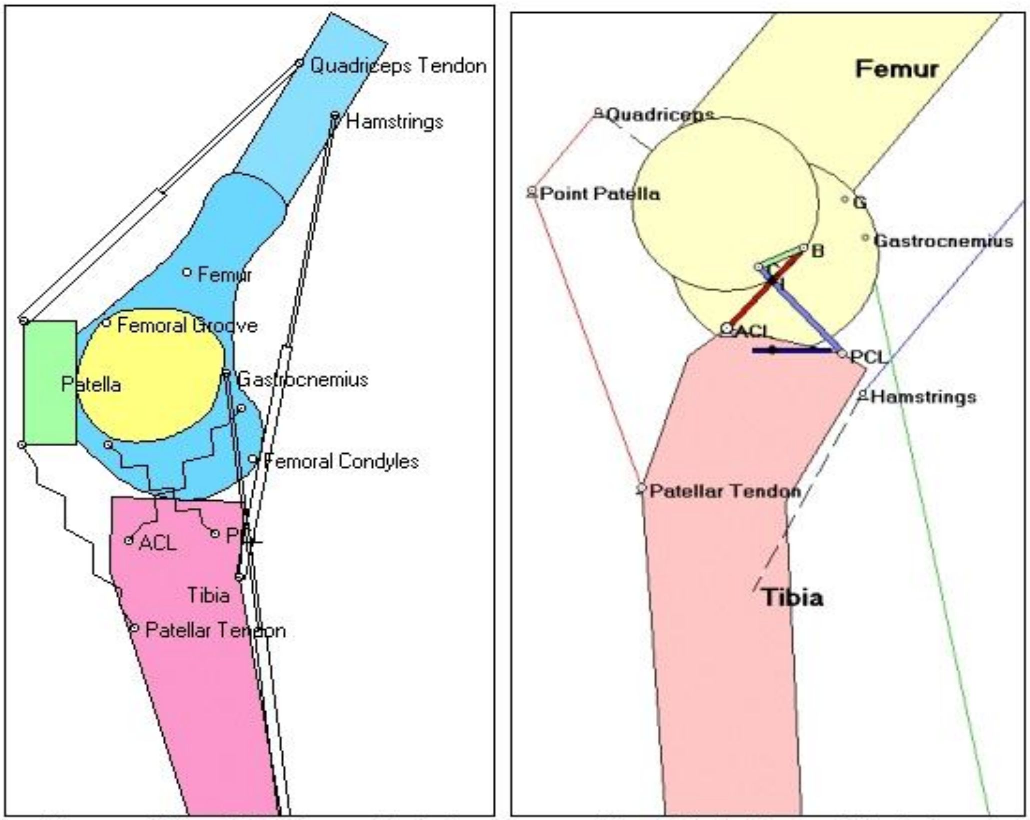


FIGURE 3.2: COMPRESSIVE FORCCE OF PATELLA[6]

Muscles apply forces to the knee joint to support its rotation in the sagittal plane and body weight. In design and development procedure of lower limb robotic devices, it is essential to study leg movements and its relation to the knee joint rotations. The longest muscle in lower limb, hamstring joins pelvis and the tibia at the back side of the knee joint [6]. Though hamstring does not play a crucial role in torque generation at the knee joint, it provides fast angular velocity during swing phase.



General Sagittal-Plane Model

Cruciate Linkage Model

FIGURE 3.3: BIOMECHANICS MODELING [7]

Another muscle, different in behaviour as compared to hamstring, known as quadriceps is situated between the middle part of the femur and front side of tibia near knee joint. Contraction of quadriceps generates compressive forces that control the moment generated by the human body weight. Compression at the knee joint is generated by the reaction force by patella ligament. This reaction force is a resultant of contraction of quadriceps occurred at the knee joint. Role of the patella is vital here because it provides connection between muscles as well as support point to limit the extensions. Features and significant characteristics of quadriceps have been considered as a motivation for many mechanical designs of exoskeletons.

From the figure 3.3, it can be seen clearly that mechanical functioning of quadriceps muscles and linear actuation type movements are similar to each other [7]. So these muscles can be represented as a linear actuator as shown in figure 3.3. Moreover, a linear actuator can determine the angle between the femur and the tibia following the contraction of Quadriceps [7].

Mechanical structure of the knee joint: The patella is situated between the quadriceps tendon and the patella tendon. Contraction of quadriceps produces a force which is transmitted to the tibia from patella by sliding motion of the femur at the knee joint [7]. For a mechanical consideration, a knee joint can be represented as a four-bar mechanism and two tendons of the knee can be considered as an equivalent springs.

3.2 THE ANALYSIS OF HUMAN GAIT CYCLE

It is essential to analyse the human gait cycles to keep clear motivation and goal of the designing and development procedure of gait devices for rehabilitation. Research of human gait cycle claims that human gait s a cycle of continuative gait process of heel strike and foot off alternatively. Different stages of human gait cycle are shown in the picture bellow. Cycle starts with the initial condition (IC) which can be defined as a moment of heel strike at the calcaneal. After IC, human gait cycle marks the starting of stance phase, which last till 60% of the gait cycle. Sub phases can be categorized from stance phase depending upon position of lower limb extremity.

Mid-stance (MST) follows the IC phase. Body weight is transferred to the sole of foot, and the dorsiflexion of ankle controls the balance of body during the mid-stance of the gait cycle. End of the mid-stance marks starting of the terminal stance (TST). TST stage is toe-off with the ground by the calf muscle. Stance phase comes to an end with the final phase, pre-swing phase (PS) where body weight starts transferring to another sole of the foot.

Gait cycle starts swing phase when stance phase is finished. In swing phase, initial phase is initial swing (IS). During initial swing, contraction of hamstring muscle and calf muscle keeps foot in the air. In the next sequence, mid-swing (MSW), body weight is transferred to the sole of foot and balance of the body is controlled by dorsiflexion of the ankle. Last sequence, terminal swing (TSW) marks the end of the gait cycle by preparing contact of foot with the ground. Just before the hill-strike, terminal swing completes the human gait cycle.

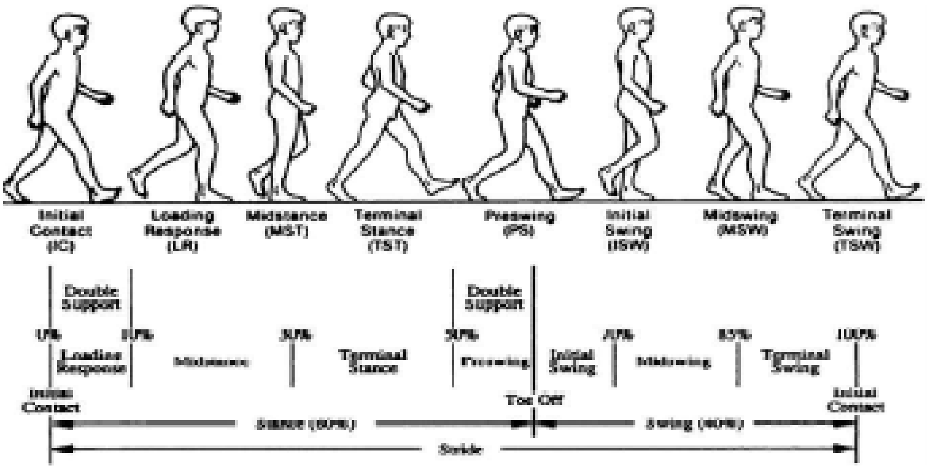


FIGURE 3.4: GAIT CYCLE [7]

During the first phase (IC) and last sequence (TST), two legs support the body, and it takes approximately 10% of the total gait cycle. Therefore, it support the starting point of stance, the phase of heel strike and starting point of swing, toe-off to consume largest muscle forces in very short time. Transition states such as initial condition (IC) that is ending point of swing phase and pre-swing (PS), starting point of stance phase that follows terminal stance (TST) are difficult for patients. These phases require power and also demands sufficient capacity to attempt the heel-strike and the toe-off in order to continue the walk [7].

CHAPTER 4: TREADMILL GAIT TRAINER

Training with treadmill gait trainer has been considered a novel and most effective approach for rehabilitation of lower limb for neurological injured patients. This group of robotic devices for rehabilitation is based on the hypothesis that states “unloading the lower limb at the beginning of training and progressively increasing the load as the gait pattern improves will enhance the recovery of posture and locomotion’’ [7]. Unloading the lower limb has been proved a critical factor in training. This approach has shown positive results in case of Spinal cord injury (SCI) patients as well as stroke patients.

Mechanism behind this effect is still unclear, but few recent animal studies have come up with the theory that states “modulation of the extensor load receptor most probably arising from the Golgi tendon organ plays role” [7]. Benefits of BWS locomotor training might result from the unloading of the lower limb during walking. This newly discovered function of the receptors needs further research.

Research studies mentioned in literature has shown that a degree of locomotor recovery is highly subject to the strategy for training of walking that the patient has adopted. Studies have suggested that use of BWS has shown more successful recovery of ambulation with respect to overground walking speed and endurance, functional balance and lower limb motor recovery. BWS system also reduces the need of physical assistance required to walk [7]. Basic strategy is, fastened the patient by harness that supports his weight unloading his lower extremities and simultaneously patient will be walking on the treadmill [8] [7].

Several researchers have conducted study experiments to compare treadmill gait training with and without BWS. Some of the results have suggested that outcome of training is also subject to the severity of the impairment. Effects of locomotor training were significantly greater in BWS group than non-BWS; where patients were more functionally impaired. No significant difference were seen between subjects suffering from chronic injury [7]. Lower pre-training scores of functional balance, lower limb motor recovery, overground walking speed and endurance claimed more benefits. On the other hand, outcomes were greater but not significantly different for BWS group than non-BWS group whose pre-training score was higher.

Kosak and Reding studied BWS treadmill therapy against physiotherapy. Results of both groups were not significantly different. However, subgroup with major hemispheric stroke patients (hemiparesis, hemianopic visual deficit or hemihypaesthesia survived patients), treated with BWS treadmill training showed greater overground endurance and velocity than physiotherapy group. So conclusion of the study was, both training methods are almost equally effective in terms of speed and endurance, but BWS treadmill training is more beneficial for hemispheric stroke patients as it is difficult for a physiotherapist to mobilize them [9].

In Cochrane systematic review studies have been performed with walking speed. Study states, there was no significant difference between with BWS or without BWS treadmill gait training with respect to speed and dependence. However, if BWS training is combined with task oriented/ task specific training, outcomes may be more effective [10] [11].

Danielsson and Sunnerhagen studied gait training and required energy consumption. Subjects those received 30% of BWS showed less oxygen consumption in comparison with a group that received training with no body weight support. This study included both stroke affected and aged healthy patients. So this study has concluded that older stroke patients (65-85 years old) could be treated effectively using WS locomotor training even if they are suffering from comorbidities such as cardiovascular problems [7]. Patients survived form stroke or SCI can receive training even in the early phase of injury if it requires low energy consumption [7]. Study experiment conducted with stroke patients revealed that 79% of stroke patients were able to tolerate treadmill training with or without BWS [7].

While treating stroke patients, it is necessary to note that BWS should not exceed 30% to 40% of body weight otherwise that may affect to the weight bearing capacity of the patient after the stroke. Data has also suggested that if the patient could carry his own weight on the affected limb with normal postures, BWS must be reduced [9].

Biomechanical studies revealed that BWS therapy prolongs the single stance period of the paretic limb. Muscle activity of weight bearing muscles also gets decreased in hemiparetic patients [12]. During studies with hemiparetic patients, that received training with the mean of 15% BWS, enabled patients to walk on treadmill more symmetrically [13], more dynamically and with lessee spasticity than overground walking [9]. Initially few researchers also thought that use of partial body weight support might be useful for the spasticity as full BWS prevents spasticity. Wearable robotic devices were invented with partial body weight support system with AAN principle that does not inhibit spasticity.

4.1 ALEX

Active Leg Exoskeleton (ALEX) is a 3 DOF device which was developed to use with Robot Assisted Gait Training (RAGT). ALEX has been developed with the concept of 'assist-as-needed' (AAN). Its force field controller applies forces on the subject's leg and gradually reduces depending on demand of the subject. ALEX is supported by the walker, so together this robotic system works as a treadmill gait trainer with force field controller.

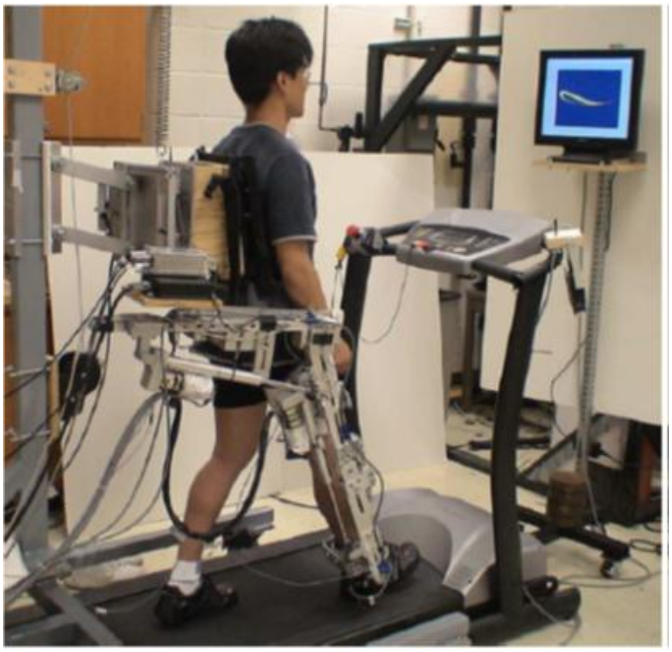


FIGURE 4.1: USER USING ALEX ON TREADMILL[14]

4.1.1 Technical Analysis

ALEX has been designed with five main components [14].

1. Walker: Walker supports the weight of the device.
2. The trunk of orthosis: this is attached to the walker. It has three DOFs; vertical, lateral translations and rotation about a vertical axis. Hip braces allow human subject to lean forward by securing human trunk.
3. Thigh Segment: This segment has two DOFs; one in the sagittal plane and the other for abduction-adduction motion with respect to trunk of orthosis. Thigh segment of orthosis can be matched with the length of a human subject by adjusting it. Thigh segment is telescopic.
4. The shank segment of the orthosis: It has one DOF that is telescopic.
5. Foot segment of the orthosis*:* It is connected to the shank of the leg where shoe can be inserted. It has one DOF at the ankle joint. Flexible design of foot segment allows limited inversion-eversion motion at the ankle.

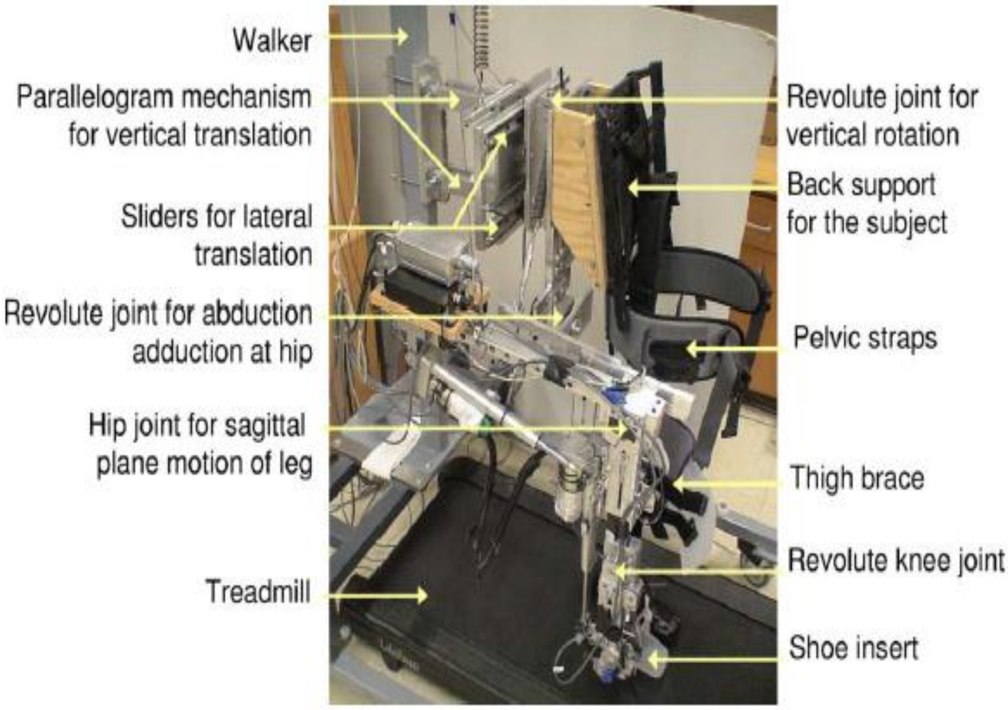


FIGURE 4.2: DEVICE ALEX WITH BASIC COMPONENTS [14]

Linear actuators actuate the hip joint in the sagittal plane as well as knee joint. Encoders that compute the joint angles are inbuilt in these motors [15] [16]. Other DOFs are passively controlled by using springs[15]. Encoder placed on the foot segment assembly measures ankle joint angle. Two force-torque sensors have been used to interface orthosis and human subject. One sensor is placed between thigh segment and the human leg. The other sensor is attached between shank segment and the foot brace.

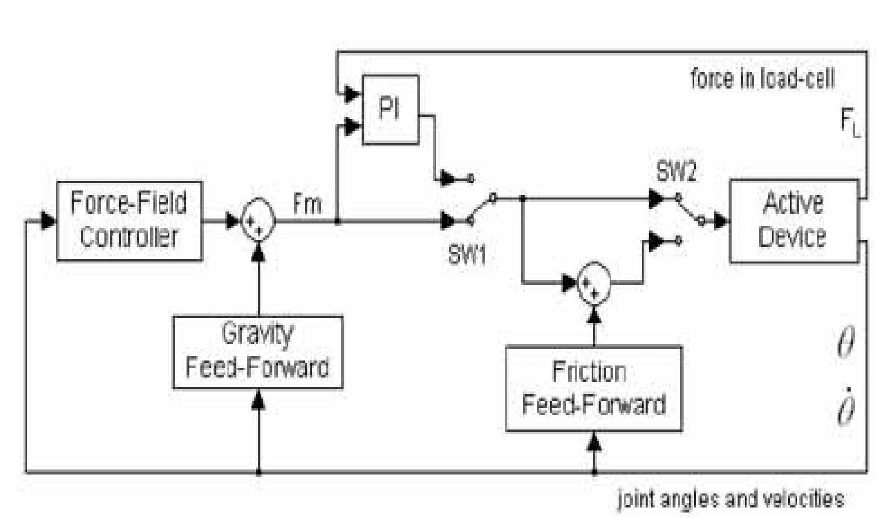


FIGURE 4.3: FORCE FIELD CONTROLLER [15]

Tangential and normal forces are applied at the ankle joint by a force field controller [15]. The aim of the force field controller is to apply force field on foot to assist or resist the motion by using gravity compensation as per requirement[15]. The torques generated at the hip and knee joints where linear actuators are placed, simulates the forces applied at the ankle[15].

For the safety, device has used the physical stops at extreme ends to prevent motion beyond allowed range of motion for each DOF.

4.1.2 Clinical Evaluation

In literature, no vast and detailed study of ALEX is available. Team of Dr. Banana and Dr. S. K. Agrawal has been working on various experiments. During 2007, experiments were performed with six healthy subjects. Purpose behind this study was to evaluate the usefulness of the device to induce short term adaption of the walking pattern in healthy subjects. Subject were divided into two groups; experimental group that received visual feedback with force field controller and control group received only visual feedback with conventional treadmill trainer [15].

Foot deviation of both groups was measured before experiments. Experimental group showed significant improvement in reduction of path deviation. Trained pattern was maintained trough out the training even after turning off the visual feedback. 60% reduction in foot deviation was recorded during pre-test too post-test evaluation [15]. In comparison with the experimental group, control group showed relatively constant results from pre-test to post-test evaluation. These results were surely inspiring, but concern was raised as treadmill walking differs from overground walking [15]. Thus further study is needed to evaluate ALEX with overground walking patterns.

In 2009, two stroke patients were studied, after three five day session subjects showed significant improvement by increasing walking speed on treadmill gait trainer [14]. Templates were used from healthy subjects for each patient. Considerable improvement was noticed in subject’s ability to match their healthy control’s template. First subject succeeded to increase template size by 20% to 85% where 20% to 100% increase was recorded with second subject [14].

In the past, robotic training used to provide fixed assistance through fixed trajectory. This approach was unable to motivate patients to correct their own abnormal walking patterns. In ALEX, visual feedback was combined with force field controller [14]. This visual trajectory continuously motivates subjects to correct their walking pattern and try to achieve more normal gait pattern. Though these results are encouraging, author has not drawn any definite conclusion as study included very small number of patients [14]. Patients gait patterns were improved significantly after the training. Among two subjects, first subject succeeded in to reduce ankle path area by 57.8% where second achieved 58.8% reductions [14].

In performed case studies, ALEX has shown inspiring results, research is needed to overcome few hurdles though such as a requirement of a large number of participants to draw precise conclusion, overground testing of patients etc. Reference trajectories (templates) were defined by using trajectories of healthy subjects. Walking trajectory for every individual human cannot be the same. Trajectory from other individual may affect the patient's natural walking pattern. No studies have addressed to this concern. Patients, who have lost total control of limbs may use ALEX to develop entirely new walking pattern.

4.2 ARTHuR

ARTHuR (Ambulation Assisting Robotic Tool for Human Rehabilitation) is a rehabilitation robotic system; that is combined with treadmill to provide body weight supported gait training. The system uses backdrivable 2-DOF parallel kinematics to move or act on the patient's foot. ARTHuR allow several walking patterns, body mass balancing is not included in this robotic system though.

Medical Discipline: Rehabilitation

Function: Active Movement of patient's leg while walking on a treadmill.

Trajectory Planning: Offline preoperatively

Kinematics: 2-DOF parallel kinematics

Kinematics type: Parallel

DOF: 2

Developed in: Irvine, CA, USA

Institute: Department of Biomedical Engineering, University of California, Irvine

Development Team: Reinkensmeyer

Status: Experimental set-up

Manufacture: Self-made robot

Arthur is based on Body-weight support on a treadmill (BWST) rehabilitation technique. This is a direct drive parallel device with a high dynamic bandwidth [16]

[17]. Literature on Arthur has stated that using simple control strategies, a highly responsive gait robot can be possibly created.

4.2.1 Technical Analysis

Arthur uses two moving coil brushless linear servomotors that drive either end of a two-bar linkage in the parasagittal plane as shown in Figure 4.4 [16]. The linkage apex is connected through a revolute joint that can be attached to the lower limb at the knee, ankle, or bottom of the foot through custom composite braces [16].

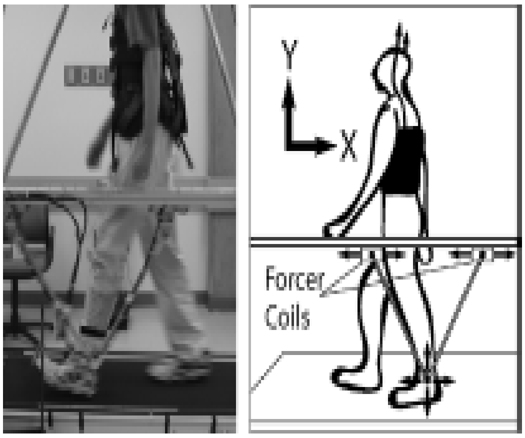


FIGURE 4.4: BASIC CONCEPT OF LOPES [16]

Ambulation-assisting Robotic tool for human rehabilitation was developed to interact with single leg during walking. The basic parameters are designed to be able to lift a large leg (~ 150 N vertical forces) [16]. It can accommodate a large step with a force bandwidth of approximately 2 Hz that is at least twice of normal human stepping. Device has remained lightweight though. It also uses a linear optical encoder with one read head per coil at a resolution of 20 µm to measure the position of moving coils [16].

4.2.1.1 Safety Features

For a safety purpose, control program at 1000 Hz is used for several safety checks. Each check creates fault condition that stops the device and the treadmill [16]. It also includes separately powered watchdog timer checks to watch on system crashes of the target computer [16]. Device also held an emergency stop button. For the final safety, an overhead frame is attached to the support harness. Harness can secure the user from falling [16].

4.2.2 Clinical Evaluation

Experiments have been performed to check abilities of the device such as backdrivability, force control ability, force field generation capability and position tracking ability with healthy subjects. First experiment tested directional ability of ARTHuR. Average directional error of -0.7° ±1.0° was recorded at a constant force of 22.2 N by ARTHuR [16]. At six different levels of force, device also produced an accurate circular pattern in the force space giving an average force error of -0.16N ± 1.75N [16]. Beyond 4 HZ, resonating supporting structure of the linear motor limits tracking accuracy. For this, frequency contents of stepping trajectory were measured, and 90% of the power spectral density was recorded below 1 Hz [16]. Backdrivability of the ARTHuR was tested with small and large subjects. Stepping trajectories of subjects were observed with and without device attached. The mean difference between the peak step trajectories for seven digitised steps was recorded. It was 2.3 cm for the small subject and .83 for the large subject [16]. Little tendency of stepping slightly higher than normal stepping were observed in subjects when device was attached to their leg. This overshoot was the result of added inertia as well as the rapid vertical acceleration of the leg at the starting of the swing phase of gait [16]. ARTHuR has proved satisfactory backdrivability, but backdrivability is limited to gross motor skills though [18].

To test the capability of the device of assisting the movement, normal stepping trajectories were recorded. Keeping device in position controlled mode, trajectories were replayed and tracking error was measured with and without subject suspended from an overhead frame. A mean tracking error of 0.74 mm was recorded without subject and with the subject it was 2.8 mm [16].

A velocity force field was applied during stepping to examine how ARTHuR can induce motor adaption. In this experiment, Leg of the subject was pushed upward by the robot when it was turned on generating direct effect [16]. Subject reduced their step height due to an adaption to the force field. Later force field was removed unexpectedly. As a result, of an ‘aftereffect’, subject’s steps were shorter than null baseline for several steps before coming to the normal baseline. ‘Aftereffect’ was the indication of subject’s adaption to predict the field through the formation of an internal model of the field dynamics [16].

All study results were supported the utility of ARTHuR for rehabilitation. A wide dynamic bandwidth was achieved through a simple mechanism and control design. Design preferred feed forward control over feedback control and good backdrivability that allowed good performance, cost reduction (due to the absence of force sensors) and without any control complexities [16]. Slight mean tracking errors and satisfactory motor adaption results were promising. So we can conclude that ARTHuR has the ability to generate a novel force field environment that induces locomotor adaption [16]. ARTHuR can reduce the assistance gradually as patient recovers following the principle of ‘assist-as-needed’ (AAN). Natural kinematic and direct feedback of movement control errors provided by ARTHuR results in rapid learning with precise movements. It can be controlled using MATLAB’s real time window target [18]. Clinical study experiments with healthy subjects have been made public. As there is no information available on clinical experiments with impaired patients; it is hard to conclude, exactly who may benefit from this device.

4.3 LOKOMAT

Lokomat is a robotic system designed for BWS treadmill gait training. The user has to be fastened by a harness, and his weight is supported by a counterweight. Robotic device moves lower extremity of the user on treadmill. The system is commercially available and clinically evaluated.

Medical Discipline: Rehabilitation

Function: active movement of patients legs while walking on a treadmill

Trajectory planning: offline preoperatively

DOF: 4

Year of development: 2002, Latest version: 2006

Developed in: Zurich, Switzerland

Institute: Automatic Control Laboratory, ETG, Zurich, Switzerland

Development team: Jezernik, Morari

Status: Commercial Use

Manufacturer: Hocoma, Switzerland

4.3.1 Technical Analysis

4.3.1.1 Construction

The Lokomat consist of two actuated leg orthosis that are attached to the user's leg. In the hip joint and the knee joint, each orthosis has one drive for the induction of the movement of hip and knee to the user[19] [20]. For this reason, the gait pattern of the Lokomat is restricted to the two dimensional trajectory in the sagittal plane [20].

FIGURE 4.5: USER WITH BWS LOKOMAT THERAPY[20]

Mechanical Lokomat hardware is consist of three actuated DOFs. Two DOFs are added to the hip joint to perform adduction/ abduction. One DOF is added to enable the device to accomplish the LPD movement. Compensation of inertial forces that the user feels because of periodic movement of the hip; is important for the user. So one additional actuated DOF is added to move the gait orthosis up and down so that compensation of those disturbing forces can be achieved.

Sketch of front view of Lokomat hardware is shown in figure 4.6 below. Number 1 and 2 shows the added linear actuators to drive adduction/ abduction and number 3 for LPD. Redundant position sensors and force sensors are attached to the linear drives. A linear drive is attached to the parallelogram mechanism to perform the vertical up and down movements. This parallelogram mechanism is attached to the orthosis.

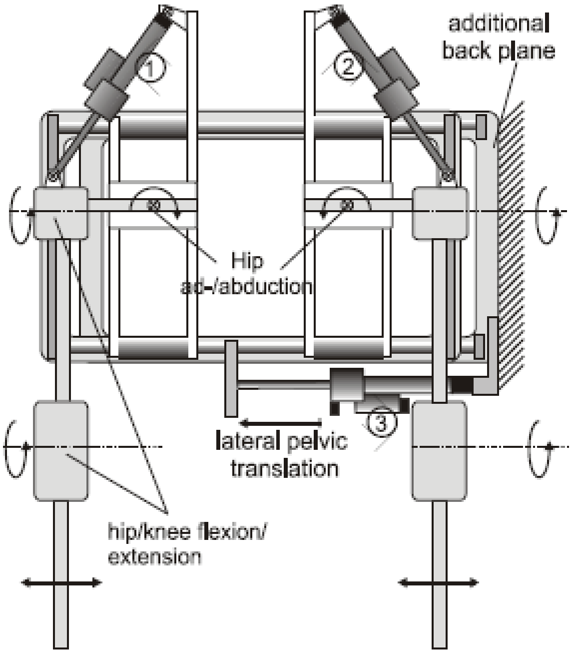


FIGURE 4.6: FRONT-VIEW OF LOKOMAT HARDWARE [20]

4.3.1.2 Control Scheme

There are three control strategies are applied: First, all DOFs are purely position controlled. Position data is recorded from the healthy subject and desired gait trajectories can be positioned using recorded data for the PD position controllers [21].

Second is method of haptic display technology. Drives follow passive spring dampers element to reduce the complexity of the system. Interaction forces present between the patient and the system can be measured by using force sensors and impedance controllers can be implemented [21]. A proportional force controller controls the interaction force with feed forward of desired value so that virtual spring damper element can be displayed to patient [21].

Third approach is to implement the adaptive position controller for the periodic up and down movement of the system. As per the individual requirements of the user, an adaption algorithm can accommodate the desired trajectory [21].

4.3.2 Clinical Studies

Since 2002, Lokomat was introduced to the rehabilitation field; numbers of experiments have been performed to evaluate the nature of locomotor gait training and its short term and long term effects. In literature, researchers have emphasized the calibre of Lokomat to provide relatively effective rehabilitation to stroke surviving patients or patients suffering from spinal cord injury.

Experiments performed with incomplete SCI patients have shown improvement of kinematic and kinetic parameters over 4 weeks of training, proving the control on voluntary movements at the ankle joint in SCI patients [22].

Robotic assisted gait training (RAGT) was used in combination with Lokomat and neurological and functional outcomes were observed in patients with subacute spinal cord injury [23]. In this case study 28 patients were treated with RAGT combined with Lokomat, and they were compared with patients with similar medical history (age, severity and level of the injury and cause of injury) those were treated in previous years. Results were based on the grounds of FAC score (functional ambulation category scale) and WISCI score (walking index for spinal cord injury). Significant difference between the points based on these scales was observed between RAGT with Lokomat and control group. Experimental group scored 30 to 20 points where control group ended with 12 to 14 points [23]. Conclusion was drawn that RAGT could be an influential addition to the Lokomat to achieve more efficient results with SCI patients.

Some recent studies have gathered evidences of acute effects of use Lokomat over conventional treadmill training, and it was expected; device affects the spatiotemporal and kinematic characteristics of walking. These studies are important in the sense of predictions of influence of devices and further improvement in on-going processes and future development [24]. Neckel and Wiseman found out in their studies with healthy subjects that maximum knee and hip flexion in Lokomat group was significantly lower than the control group; but maximum hip extension was also higher in Lokomat group, which could affect walking gait pattern [24]. This study also noted that hip extension during terminal stance, which is the primary goal of the locomotor training [24].

Studies performed with sub-acute stroke patients did not show significant differences between Lokomat group and control group. Both groups were compared for FAC, BI (Barthel Index), MI (Motricity Index) and body composition (body weight and fat mass). Among these, only difference was recorded between the experimental group and control group in body composition. Control group showed an increase in body weight and fat mass where experimental group did not show any changes in body weight but exchanged fat mass for lean body mass [24].

Similarly, in the other case studies, sub-acute stroke patients did not show significant greater improvement in over ground walking speed. Results for balance, walking ability and motor impairments were not different for both groups.

On the other hand, experiments done with severely disabled patients due to stroke showed significant differences. Experimental group (Lokomat) and control group (conventional therapy) were judged with aspects of FAC, NIHSS (National Institute of Health Stroke scale), FIM cognitive, FIM motor, SAS (stroke activity scale), gait velocity, TUG (timed up and go) and exercise tolerance. In FIM cognition and SAS testing, no considerable differences were recorded between both groups [24]. FAC, NIHSS and FIM motor tests resulted in greater improvements in the experimental group rather than the control group [24]. Even with stair climbing test, that was performed to evaluate velocity, exercise tolerance and TUG; the experimental group showed greater improvements in comparison with the control group [24].

Lokomat therapy has proven better performance in severe stoke patients than sub-acute stroke patients. There were no significant differences between the control group and experimental group of sub-acute patients. So for sub-acute stoke patients conventional therapy also can be useful as they can easily be assisted manually.

Lokomat has shown significantly positive results for spinal cord injury patients as well as Parkinson's disease [25].

4.4 LOPES

Lower extremity power exoskeleton is designed with 8 DOF and used in combination with treadmill. Unlike the previously invented robotic devices, this device uses selective support algorithm to provide assistance for various task specific rehabilitation training. Joints of LOPES are actuated with the Series Elastic Actuators (SEA). LOPES is designed with the network of Bowden cables.

Medical discipline: rehabilitation

Function: leg and hip rehabilitation, gait training

Trajectory planning: offline preoperatively

Kinematics: 3 DOF per leg, 2 translational DOF for the pelvis

Kinematics type: Serial

DOF: 8

Years of development: 2007

Developed in: Enscheda, Netherlands

Institute: Laboratory of Biomedical Engineering, University of Twente

Development team: Ekkelenkamp, Van der kooji

Status: Experimental use

Manufacturer: Self-made robot

4.4.1 Technical Analysis

4.4.1.1 Construction

LOPES is the combination of a freely translatable and 2-D actuated pelvis segments along with a leg exoskeleton that contains three actuated rotational joints; two joints at the hip and one joint at the knee. These joints are impedance controlled so that it can allow bidirectional mechanical interaction between the robotic system and the user [26].

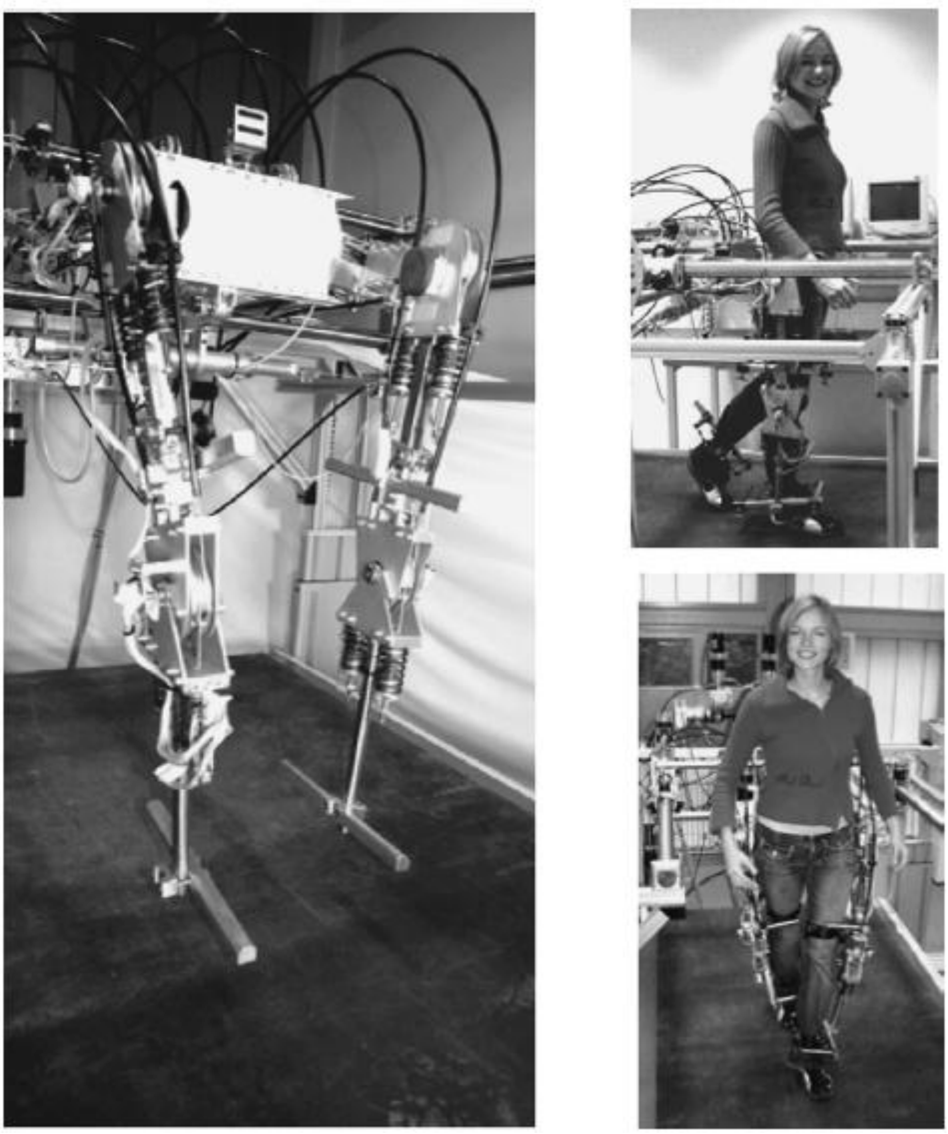


FIGURE 4.7: LOPES FROM DIFFERENT ANGLES [26]

Possible modes of training [27]:

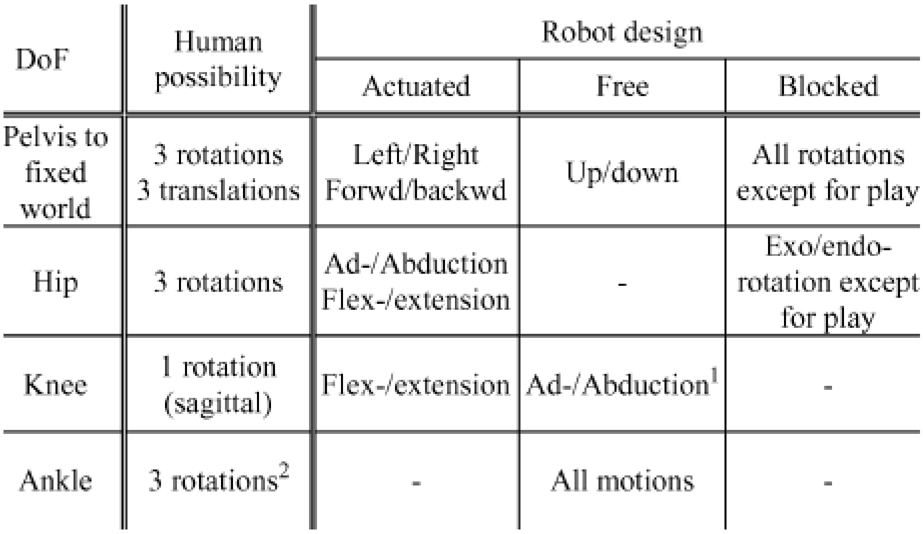
1. The patient in charge

2. The robot in charge

These modes decide whether robot would follow or guide the user respectively.

Table given bellow describes all possible DOFs for human and all actuated, Blocked, left free DOFs in the device as well. The ankle joint has been omitted as external ‘ankle-push-off’ was not necessary in the device for a safe walking. Also, substantial torque applied to the feet can be possibly painful at least without fit-to-size foot interface used individually. Pelvis actuation can be assured the user’s forward progression. Necessary ankle function for the safety purpose is to assure foot clearance during swing. To make sure this clearance, simple strategies can be used such as elastic straps or passive orthosis.

TABLE 1 ACTUATED, FREE AND BLOCKED DOD OF LOPES EXOSKELETON [26]



DoF	Human possibility	Robot design		
		Actuated	Free	Blocked
Pelvis to fixed world	3 rotations 3 translations	Left/Right Forwd/backwd	Up/down	All rotations except for play
Hip	3 rotations	Ad-/Abduction Flex-/extension	-	Exo/endo-rotation except for play
Knee	1 rotation (sagittal)	Flex-/extension	Ad-/Abduction[1]	-
Ankle	3 rotations[2]	-	All motions	-

LOPES is the device with 8 actuated DOFs which provides forward stepping motion and maintains fundamental instability for walking or standing positions of human; User of the robot (when needed) should control the balance [26]. One unactuated DOF is for the vertical motion of the pelvis which is passively weight compensated as ideal spring mechanism [26].

To connect the exoskeleton to the fixed world, it requires:

1. A height adjustable frame so that it can be matched to the height of the user. After adjusting this height at the beginning of the training session; it will be fixed during the rest of the session [26].

2. Two sets of perpendicularly placed parallel bars with carriage for the forward/backward and the sideways motion; double bars are used to translate load torques into forces [26].

3. A parallelogram with bearings and weight compensation to allow limited vertical motion during operation. The weight compensation is realised with as 'ideal spring mechanism' [26].

This construction is then placed atop treadmill. Motors are placed back at the construction and attached to the robot joints by two Bowden cables per actuated DOF.

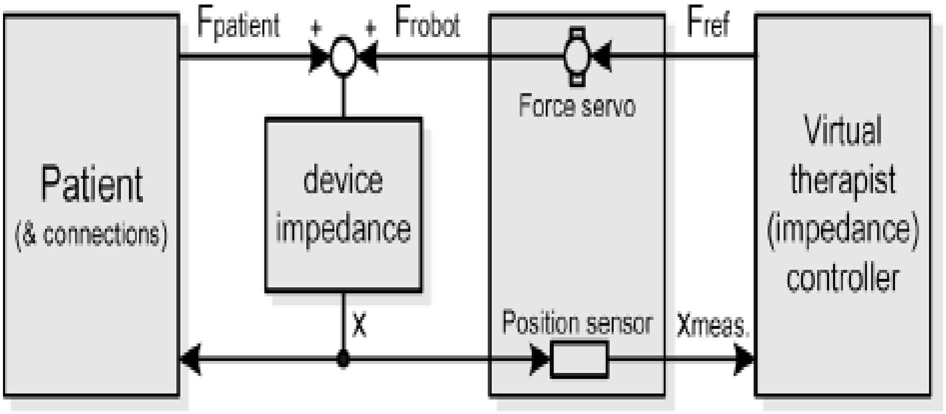


FIGURE 4.8: BASIC OUTLINE FOR IMPEDENCE COTROLLED DEVICE [26]

Above figure 4.8 is the basic outline for an impedance controlled device that is applied on robotic system. Connections between the robot and user are assumed as a part of user impedance, in order to consider that the device is connected to the user. Here, F indicates force and X indicates position [26].

Impedance controlled exoskeleton: exoskeleton type robot was developed to apply correction forces or torques on user's legs. As robotic exoskeleton moves parallel with human exoskeleton, it reduces the need of the additional DOF or motion ranges to follow the user's motions [26]. This correspondence between joint motion of the robot and the user makes it relatively easier to implement mechanical safety limits into exoskeleton structure. Shortcomings includes demand of accurately align joints and necessity for high torques. The exoskeleton is attached to the actuated support at a pelvis height in order to apply correction forces at pelvis and for a weight compensation of exoskeleton [26]. This design makes LOPES a combination of exoskeleton robot for legs as well as end-effector robot for the pelvis.

4.4.1.2 Control Scheme

Two different strategies have been used for LOPES. Complimentary limb motion estimation (CLME) [28] and the virtual model control (VMC) [29] [30].

Complimentary limb motion estimation (CLME) analyses dependencies among human DOF in subjects. CLME determines the intended motion of paretic or amputated limbs by identifying the motion information of sound limb [28]. Evaluation of this control scheme has been proved effective for functional walking patterns in healthy subjects [28]. Further investigation is needed to test efficacy of the CLME in impaired subjects.

Control system VMC has been studies in order to improve interaction between the patient and the robot [27] [30]. VMC is compact, simple (requires no complicated computation) and implementation in distributed manner is possible. VMC defines physical interaction with subject, predicting required rehabilitation; and transfers this interaction to the virtual physical models such as dampers, springs etc. These virtual models can provide the required amount of support [27]. This approach is effective as it separately modifies selected gait characteristics. For virtual model controller some goals are considered [29]:

1. Unhindered walking
2. Postural stability of the patient
3. Sufficient weight bearing
4. Support weight bearing
5. Increase the speed of walking

LOPES is being redesigned for advancements and modifications. Future developments will be based on: 1. Mechanical design and control of LOPES to provide more stabilisation 2. Extension, refinement and testing the controllers to provide selective subtask control 3. Development of feed-forward controllers.

4.5 CLINICAL EVALUATION

Clinical experiments only have been performed on healthy subjects yet. Though primary function of robotic devices is to provide assistance for paretic limb, it is also expected that device should not hinder the movements of the patient when no assistance is provided. To testify this requirement, LOPES was tested with ten healthy subjects. Evaluation was done with respect to gait parameters, kinematics and muscle activity of patients [31]. LOPES was on transparent mode where no assistance was provided to the subjects. Muscle activity, patterns of joints and segment movement with LOPES resulted in a similar pattern with free walking (normal pattern). However, concern was raised because inertia was added to the subject’s leg by the attached exoskeleton [31]. Manipulation of this inertia by the subject was necessary. Moreover, inertia was responsible for decreasing knee flexion during swing. Aside from the added inertia, subject also experienced some resistance in movement of pelvis during training. This resulted in an increase of frontal trunk rotation.

At the last, overall performance was satisfactory. An observed walking pattern developed with the LOPES training was almost similar to the normal walking pattern [31]. Despite of satisfactory results, reduction in inertia of exoskeleton or compensatory algorithm programs are needed to achieve unhindered walking while using robotic system at transparent mode.

The other study experiment was performed with ambulatory chronic stroke survivors to evaluate the utility and scope of the DOFs of the device for the stroke patient [31]. Patients participated in this study had stiff knee gait, a gait abnormality often found in stroke survivors in which amount of knee flexion gets decreased during swing phase [31]. This study was also performed on transparent mode, with no assistance provided so that subjects were free to follow their own walking pattern without any force applied by the device. Lower knee flexion range was recorded in paretic limb compared to non-paretic limb. This was compensated by using a hip circumduction strategy which resulted in hip abduction [31]. So results claimed, lower the knee flexion higher the hip abduction. Whole experiment demonstrated that subjects could follow their own motion strategy while using the device and they can experience their self-generated activity [31].

LOPES was also tested for feasibility, to support a specific subtask in healthy subjects. Tasks were foot clearance, weight bearing and large stepping. Subjects received training with LOPES without any support. Method of evaluation of feasibility was based on the how well the set references values were attained and how the support affected the remaining of the walking pattern [31]. The support of the step length showed significant extension in length, but at the same time decrease in step height was also recorded [31]. Exerted robotic torques might be the reason behind this as device exerts the hip and knee extension torques to increase the step length. To overcome this unwanted effect, two separate support algorithms were combined; support of step length was combined with support of step height, and it resulted in increase in not only step length but also step height [31].

Weight bearing subtask supported by the robotic gait trainer is more advantageous than conventional overhead suspension systems. Gait training systems have shown some disadvantages too. These disadvantages can be compensated by robotic exoskeleton [31]. During the feasibility testing of LOPES, selective support control algorithm exerts torques on the subject’s joints to compensate the gravitational torques and thus preventing knee buckling. LOPES with VMC has resulted effective in rehabilitation even with performing subtasks [27]. Limitations associated with VMC; stiffness and bandwidth are not severe compared to its advantages. So we can conclude that LOPES is an effective device which is able to accomplish assist as needed behaviour in order to provide more effective rehabilitation training.

LOPES with nine DOF give freedom to the patient to use only DOF those needed. Unnecessary motors can be detached from the exoskeleton that makes it lightweight exoskeleton [30]. Experiments performed with LOPES have given encouraging results in functional walking patterns, performing subtasks, safety and feasibility in using this device etc. Different controllers working together can be an advancement for this device in the future [30].

CHAPTER 5: ACTIVE FOOT ORTHOSIS

Active foot orthosis are actuated exoskeletons that have to be worn by the user to get assistance in walking overground or on a treadmill. This type of devices are normally be used in combination with treadmill gait trainers or exoskeletons for rehabilitation [32].

Definition of orthotic states ‘it a specialised mechanical device that supports or supplements weakened or abnormal joint or limbs’ [33]. Active foot orthosis includes actuated ankle orthosis, knee orthosis and hip orthosis. These orthosis devises are designed to provide stability, to apply desired pressure and maintain proper alignments of the joints [33]. Robotic advancements in these devices enable devise to resist unwanted or over extended motions of joints by applying a form of tension. Robotic devices designed with actuators and force-feedback provides excellent resistivity and operability that can be used for a muscle enhancement and augmentation [33]. These types of devices offer rapid recovery as well as efficacy at restoration of biomechanics and improvement in muscle functionality.

Addition of the torsion springs, piston or few simple mechanical devices belongs to Semi-active devices where semi active devices become ‘active devices or power devices’ with the addition of actuators [33].

As compared to passive orthosis and semi-active orthosis, design of active orthosis is complicated, but these devices are ideal due to their dexterity to cope up with real time while providing support to the joints [33]. In a broad sense, exoskeleton is nothing but a set of various active orthosis.

5.1 PAM & POGO

PAM (Pelvic Assist Manipulator) is a robotic device for patients who need rehabilitation for a pelvic bone. Two versions of PAM have been designed. PAM uses parallel kinematics with 7 length variable pneumatic struts and a counterweight for balancing the patient during his/her training session on a treadmill [34]. Second version uses 4 pneumatic struts [34].

Medical Discipline: Rehabilitation

Function: Active movement of patient's hip while walking on a treadmill.

Trajectory Planning: offline preoperatively

Kinematics: parallel kinematics

Kinematics type: parallel

DOF: 6

Years of development: 2002

Developed in: Irvine, CA, USA

Institute: Department of Biomedical Engineering, University of California, Irvine

Development Team: Reinkensmeyer

Status: Experimental set up

5.1.1 Technical Analysis

5.1.1.1 Construction

PAM has been developed to measure and manipulate pelvic motion during gait training session on a treadmill. PAM is actuated by 6 pneumatic cylinders. Its combination with a non-linear force tracking controller provides backdrivability [35]. It also provides large force output at a lower cost. PAM can be used as a 'teach and replay' device with the use of PD position controller. Position controller drives pelvis onto the desired trajectory with or without assist of therapist. Foot switches were introduced for the detection of the gait timing [35]. A feedback algorithm was introduced for the adjustment of the play back speed of the gait pattern.

PAM is made up of a pair of 3 DOF pneumatic robot that is joint to the backside of a harness attached to the user. In this pair, each sub robot is consisted of tripod configuration with 3 pneumatic cylinders [35]. Axes of these cylinders intersect at a point passing through a custom designed joint structure. Those both joints are attached to the belt through a universal joint mechanism again whose axes intersect at the same point [35].

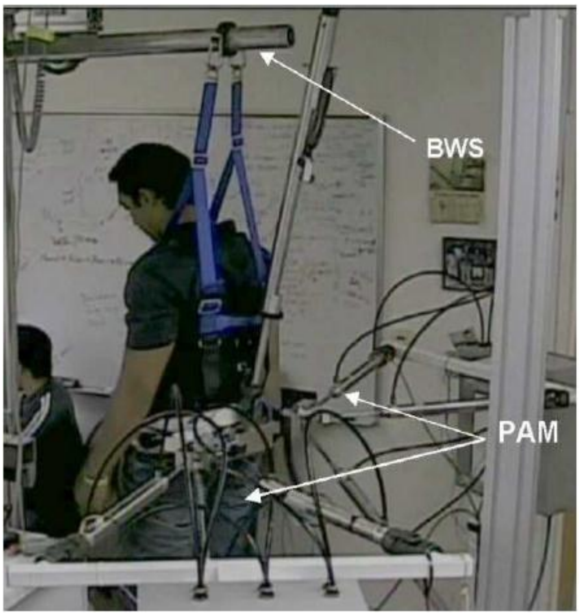


FIGURE 5.1: **GAIT TRAINING WITH PAM [35]**

PAM has five actuated DOF among which 3 are translational, and 2 are rotational. One passive DOF for pelvic tilt is not controlled or measured. A separate Body Weight Support System unloads user which allow him/ her to mimic naturalistic motion while providing accessibility to the therapists and user's entry. PAM is backdrivable and it has managed to produce large forces at lower cost; $1000 per DOF [35]. At 40-50 PSI supply pressure, in a horizontal plane it can roughly generate 150 lbs and 75 lbs in a vertical plane. Foot switches are added to measure loading on the feet. Force sensitive resistors are attached to the probes. Also, supporting rubber material is inserted beneath the heel in the shoe [35]. These probes are linked to the control PC via an interface circuit that transmits loading/unloading signals (digital signals) by utilising adjustable threshold detection [35].

5.1.1.2 POGO

Pneumatically Operated Gait Orthosis (POGO) is designed specially to use it in combination with PAM. For leg swing, POGO provides assistance. Without imposing any abnormal constraints on normal walking motion, it can also prevent buckling of the knees in stance phase [36].

POGO has two actuated DOF at each side (The hip and knee), and one passive DOF to support naturalistic leg motion. It allows motion in parasagittal plane (hip abduction/adduction). An attachment braces provide additional passive DOF. Braces are designed in such a way that they imitate the actual hand placement used by trainers [36]. This design has several advantages [36]:

- It uses Pneumatic cylinders that are inexpensive and relatively lightweight.
- Knee cylinders do not hyperextend the knee.
- It accommodates pelvic swivel and tilt as an entire system is referenced to the hip belt.
- Leg attachment braces imitate the actual hand placement of therapist.

5.1.1.3 Control Strategies

Control strategies were applied to pneumatic actuators by McDonell. Matlab Simulink and PC are used for the implementation of the real time control task with a sampling rate of 500HZ [35]. Force tracking controller and position controller are tested with simulation [35].

Purpose of teach-and-replay concept was to provide no or minimum support given by therapist if the user is closely maintaining desired trajectory and provide more assistance as per need if the user is deviating from desired trajectory [35]. Authors recorded the pelvic trajectory while stepping in backdrive mode. Identification of step cycles and taking an average made computation of a mean trajectory pattern possible [35]. Sequence of this mean trajectory was replayed repeatedly using position controller. Experiment of teach- and- replay was successful with 100 lbs punching bags. When unimpaired subject was taken for experiment (mean trajectory pattern was sampled from his own stepping), problems occurred [35].

As a human tendency, subject could not maintained same trajectory even during stable walking with the same speed of the treadmill. As mean trajectory pattern was fixed, and the device was replaying that sequence repeatedly, this situation emerged de-synchronisation between subject and device [35]. As therapists possess, device lacks tactile and visual senses which can determine in which gait phase the subject is. Solution is synchronisation algorithm with foot switches to detect step timing. This synchronisation algorithm achieved stable synchronisation with varying step size and period [6]. Figure 5.2 shows the summary of a complete algorithm except some saturation blocks and logic that actually have been implemented in device for safety purpose.

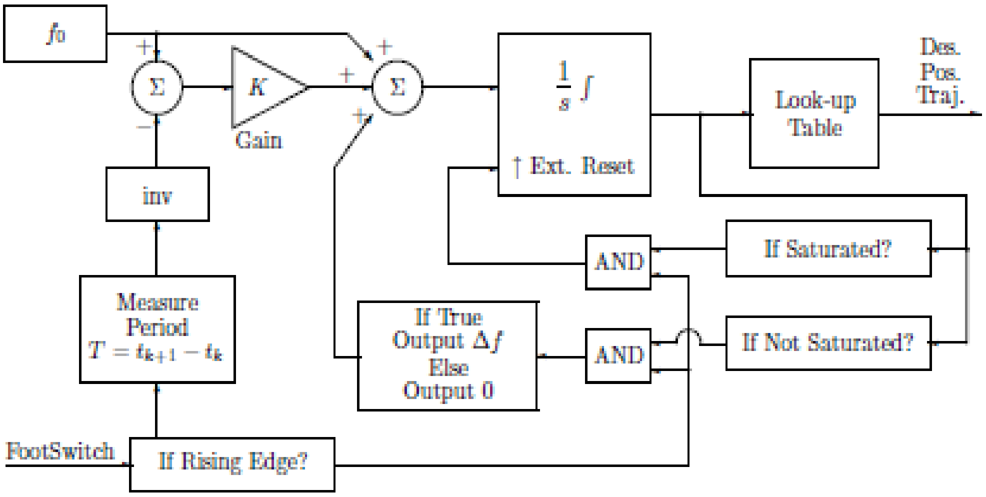


FIGURE 5.2: **SUMMARISED CONTROL ALGORITHM [35]**

Pneumatically Operated Gait Orthosis (POGO) was attached to PAM later, in order to detect gait phase easily and accurately.

5.1.2 Clinical Evaluation

Experiments were conducted to substantiate the feasibility of the basic design of PAM and POGO and the controller. Experiments also affirmed accessibility of the device for the wheel chair, utility of pneumatics in a training environment and the adjustability of the technical braces [37]. Control schemes, ‘teach-and-play’ and ‘real-time synchronization algorithm’ were also testified [37].

Experiments were conducted in six stages on three unimpaired subjects and five chronic spinal injury survivors. In stage (A) only EMG and foot switch signals were recorded with no robotics assistance [37]. During this warm up, manual assistance was provided as required. In stage (B) pelvic trajectory, EMG and foot switch signals were recorded for 30 s while PAM, in backdrivability mode was attached to the subject [37]. At the beginning of the experiment, unimpaired subjects were asked to exaggerate the pelvic motion and SCI subjects were assisted by the therapist to be stable and perform as normal as possible movement of pelvic and legs

[37]. Using recorded kinematics data mean trajectory was computed. This mean trajectory was used as a reference trajectory for the rest of the experiment. During stage (C) and (D), system was tested for replay mode, replaying mean trajectory with and without synchronization algorithm respectively [37].

POGO was attached in addition to PAM in stage (E). POGO was set on the backdrivability mode while PAM replayed mean trajectory synchronously, thus mimicking the actions of trainer [37]. Again, mean trajectory was computed from the dated collected from POGO and PAM, this mean trajectory was used as a reference trajectory for the next stage of an experiment [37]. In the last stage (F), POGO and PAM provided active assistance with synchronization.

Results of the experiments satisfied the primary objective of feasibility. Both, unimpaired and SCI subjects could tolerate the device comfortably (without any previous exposure to it). During experiment, abundant time was spent (about 30 minutes) for reach patient to adjust and attach braces [37]. This physical interface between human and robot needs further research.

This robotic system effectively served a function of motion- capturing. All recorded trajectories of each individual were unique for both; unimpaired and SCI subjects. These results illustrated a need of unique reference trajectory, tailored for individual referring his own motion pattern rather using fixed trajectory recorded from other subject [37].

Problem of de-synchronisation was faced during fixed speed ‘teach and replay’ mode with each subject. Following the human tendency, subject could not maintain the same speed and motion pattern throughout the training. So fixed speed policy of the system forced unexpected forces on the subject to maintain synchronisation when he walked shorter or quicker. Subjects reacted against these unexpected forces to gain stability which resulted in shorter stepping. This hurdle was cleared with the use of synchronisation algorithm, providing consistent power assistance by analysing the robotic power and work. PAM with synchronisation gave satisfactory results by adapting and repeating the actions of therapist. POGO was faced little criticism for complexities of attachment and adjustment of knee and ankle braces [37].

PAM and POGO undoubtedly have calibre to improve the effectiveness of rehabilitation therapy while relieving the therapist from workload.

CHAPTER 6: WIRED ROBOT

Motivation behind the innovation of cable driven robot is short comings of available robotic devices. Cable driven robots are the combination of body weight support and task specific training devices [38]. These devices have been designed with the structure of conventional BWS treadmill gait trainers, but instead of heavy actuators it uses actuation links (wires/ cables) driven by motors that can apply pulling forces only [39].

In recent years several studies have demonstrated effectiveness of use of robotics in the field of rehabilitation. Numerous robotics devices based on BWS treadmill training, foot plate manipulator concepts have been proposed till a date. These devices have some limitations too. These limitations were the motivation behind a creation of cable driven robotic system that would provide safe, flexible and human friendly rehabilitation [40]. Another important feature of this type of devices is devices motivates user to use his ability to balance himself. Cables generate tension as a minimum as possible, providing user to take the initiative in muscle movements. Cable tension can be reduced further or increase as needed to maintain the user's safety.

This concept is comparatively new in rehabilitation. Not many devices have been designed or manufactured. Couple of them such as SRING-MAN and NeReBot (Neuro Rehabilitation Robot) have been mentioned in the literature [41]. Despite its requirement of complicated kinematics and dynamic models, results of evaluation tests were encouraging. These devices can be used to train bedridden, nonambulatory patients too [40]. Other than rehabilitation, cable driven robots are topic of attraction for sport simulation also [42]. Further clinical studies and development is needed.

6.1 STRING-MAN

The system STRINGMAN is a robot for patient mobilization on the treadmill. It uses cable-driven kinematics to provide rehabilitation by means of supporting the patient's upper limb in 3 DOF. System Controls forces in the limbs. Synchronisation of movements can be achieved by synchronisation algorithms. Information on clinical experiences is not available.

Medical Discipline: rehabilitation

Function: active movement of patient's upper part of the body while walking on a treadmill.

Kinematics: wire-kinematics

Kinematics type: parallel

DOF: 3

Years of development: 2003

Developed in: Berlin, Germany

Institute: Fraunhofer IPK

Development team: Rolf Bernhardt

Status: Experimental set up

Manufacturer: Self-made robot

6.1.1 Technical Evaluation

6.1.1.1 Construction

Approach of the development of STRING-MAN was towards interactive, light-weight gait rehabilitation devices. STRING-MAN is an active weight bearing balanced system. STRING-MAN is a powerful robotic system which can restore motor functions with a combination of partial body-weight bearing (PWS) technique and robot controlling functions [38]. The design based on the 'string-puppet principle' has overcome the shortcomings of partial weight bearing system such as posture control, weight bearing and balancing [38].

STRING-MAN is a wired robot, and these wires can be attached to the human trunk and pelvis through the user interface (harness, corsage). Device controls the posture in six degrees of freedom. Depending on the various training modes and related gait patterns, device balance the weight on the legs [38]. This device can sense the interaction forces on the legs so that it can identify how much efforts the user is applying. As per his need, system can apply force or an impedance control in order to uphold his initiative [38]. To control the interaction is an important feature of STRING-MAN.

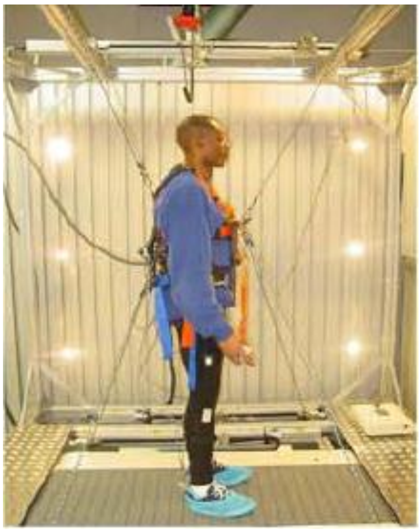


FIGURE 6.1: STRING-MAN DEMONSTRATION [38]

At the beginning of the training session, tension of harness belt can be hold at a minimum level. So that, the user can conceives his or her balancing capacity. Control system of the device can increase tension smoothly in order to prevent patient from falling or loosing balance [38]. Within a sufficient time STRING-MAN can uphold user safe. Another important feature of this device is it can bring the user in initial position during rehabilitation. This provides an opportunity to observe the body's capability to balance. Training to the trunk for stabilisation on legs is also possible.

As per the requirement of Kinematic and dynamic modelling tools, MATMAN was developed. MATMAN was the gait modelling toolbox designed in MATLAB to support STRING-MAN development [38]. MATMAN is consists of 40 DOF with adjustable height and weight. 40 DOFs are: 7 per extremity, 6 for trunk-head chain and pelvis. Figure 6.1 shows a dynamic model of STRING-MAN.

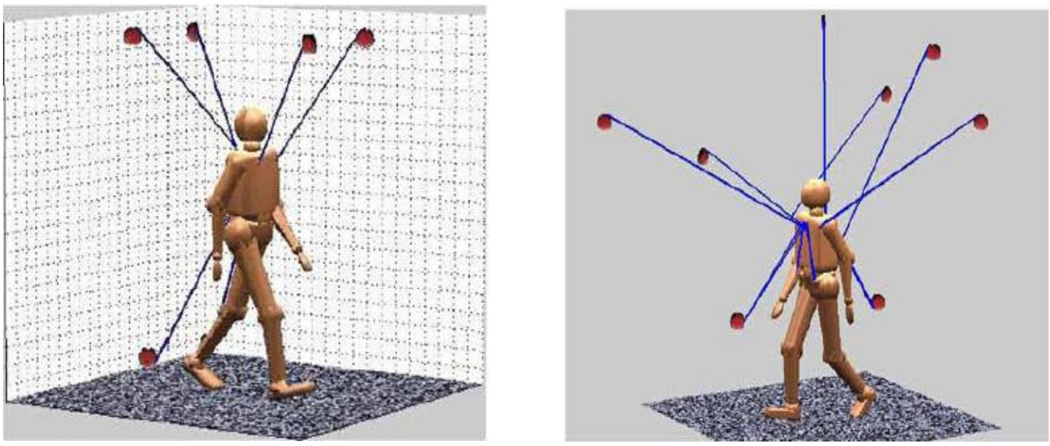


FIGURE 6.2: OPTIMAL WIRE ROBOT WITH TRUNK AND PELVIS ATTACHMENTS (LEFT) AND MATLAB REHABILITATION WIRE ROBOT DEVELOPMENT ENVIRONMENT [38]

Figure 6.2 is illustrating body weight support concept with cable tension. Number of applied wires is kept higher by one than numbers of controlled DOF in order to maintain wire tension. Wire tension should be maintained without in correlation with Cartesian loads such as gait dynamics or weight-bearings.

During weight bearing, to compensate the spine loads, system with 10 wires was introduced. As its user interface is more complicated, string-man with 7 wires is considered to be more reliable.

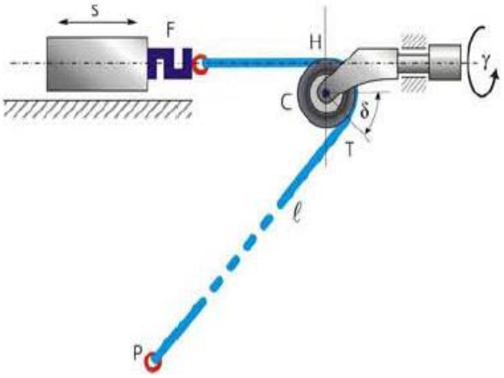


FIGURE 6.3: WIRE DRIVE CHAIN [38]

Figure 6.3 shows a wire drive chain. This kinematic structure is a representation of the wire length that controlled by a linear drive via a pulley. It consists of pulley pivot sensor and the force sensor which are used to control interaction between user and the computation of wire end-point position.

6.1.1.2 Interface between Human & Robot and Sensory System

Pelvis harness that is designed for the user's comfort during a training session is the key component of user interface of STRING-MAN. Pelvic harness is used to decrease displacements (skin effects) created by higher weight bearings and tensions in the wires. Despite all considerations and precautions taken during development of human-robot interface, it needs more development to fulfil further effective rehabilitation requirements such as flexible adjustment, rapid attachment, user's comfort etc.

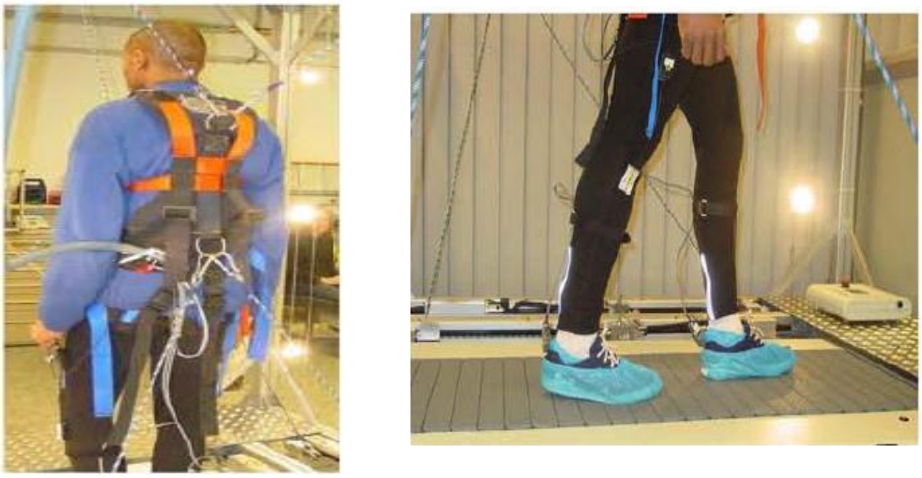


FIGURE 6.4:A)PATIENT-MACHINE INTERFACE B)FOOT GAIT PHASE DETECTION SENSORS [38]

Sensory system of the STRING-MAN includes a foot gait-phase detection sensor, zero-moment point estimation sensor and reaction force sensing estimation sensor, wire force and linear actuator position sensors, knee goniometer and pulley sensors. Computations of Cartesian body forces, Cartesian positions of wire intersection points can be done with the support of integrated wire sensors. These all computations are possible without actual measurements of bio mechanic parameters and user geometry. The gait phase detection system includes various force sensitive resistors. The gait phase detection sensor system is shown in figure 6.4B. This system identifies normal gait phases, four walking phases; heel-strike, swing, heel-off and stance as well as abnormal gait phases which arises during walking of impaired subject. The gait phase detection system also provides important information regarding monitoring attributes for weight bearing in the stance phase.

Hurdle between human-robot interfacing is no rigidity in connection. Kalman filtering technique is used to compensate measurement noise and drifts, high dynamic inertial motion unit (IMU) and the fusion low bandwidth wire positions.

6.1.1.3 Control Algorithm

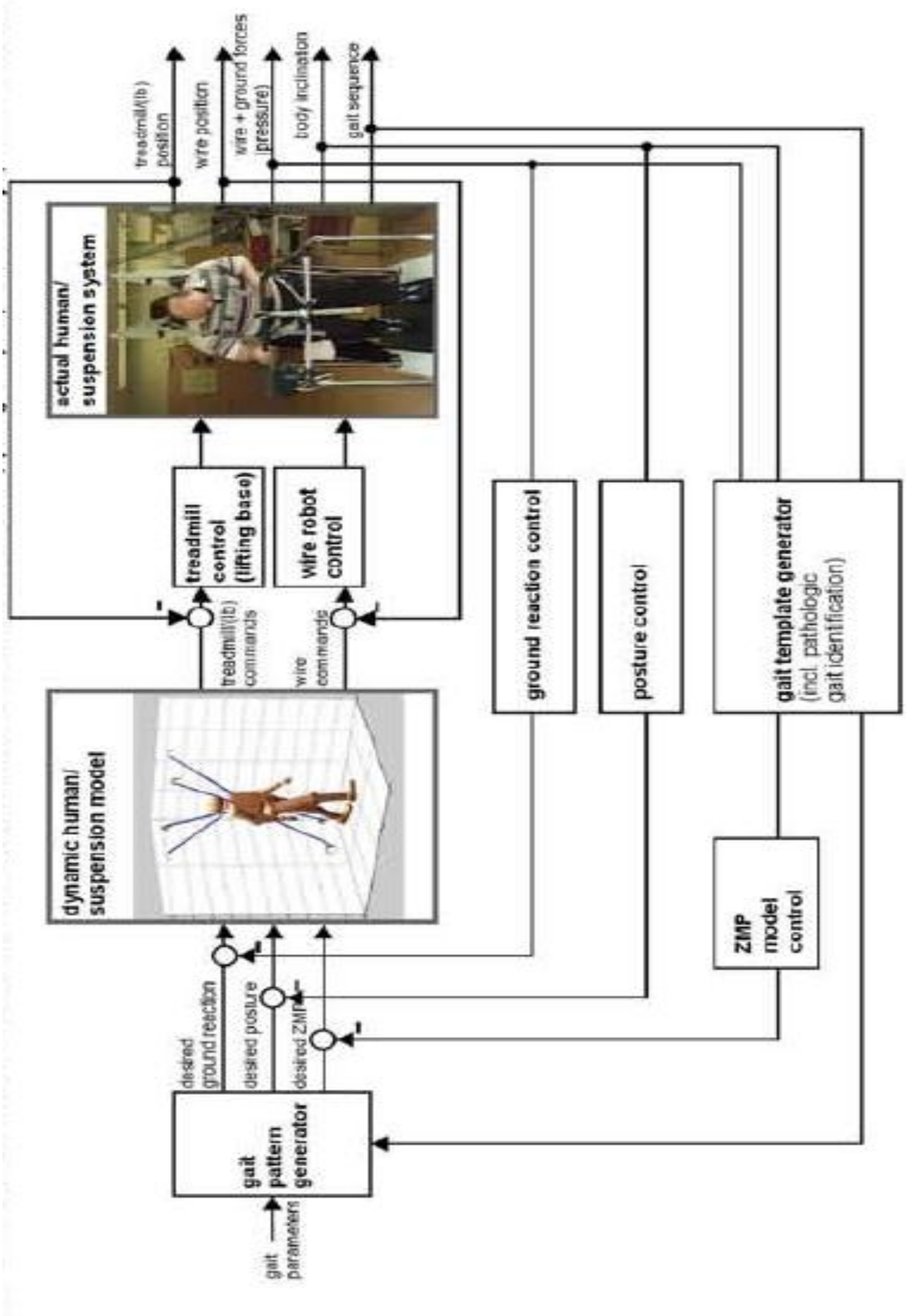


FIGURE 6.5: CONTROL ALGORITHM [38]

Control system of STRING-MAN is based upon ‘Zero moment point (ZMP)’ concept. Measurements of foot reactions and wire force are used to estimate and control the ZMP. STRING-MAN control system is composed of a complicated structure which has several control loops such as gait posture, treadmill control, reaction force and internal wire robot. The basic gait pattern generator is also included in STRING-MAN Control system to generate desired human gait pattern and ZMP location online. Actual data is compared with estimated values and control feedback is closed using Cartesian models. To motivate user’s own initiative, Interactive control system is designed.

The STRING-MAN drive system prevents the user from falling during control shut-down. Complicated wire structure is the main concern for safety measure [38].

CHAPTER 7: FOOT-PLATE MANIPULATOR TRAINING DEVICES

Footplate manipulator training devices are not significantly different from a treadmill gait trainer. This type of devices has footplates to hold feet of the user to robotic manipulator mechanism. This robotic mechanism provides body support and lifts the user's body so that the user can user can imitate walking pattern.

As discussed in a previous section, treadmill gait trainer devices have been proved more efficient way to provide rehabilitation than conventional therapy. It has some disadvantages though. There is a difference between walking on a treadmill and overground walking. Patients who received treadmill gait training showed positive results during evaluation. However, they could not perform better on overground. This limitation leaded new concept of footplate manipulator where user can actually feel the sensation of overground walking.

Basic construction includes a frame to support body of the user and footplates to hold the user's feet. A frame incorporates harness and braces to ensure user's safety and security. Trajectories of the footplates can be programmed to imitate various walking situations such as walking on the ramps, tripping, climbing up and down stairs etc. [43]. In several case studies Foot-plate manipulator devices have been proved more effective that treadmill gait training with body weight support [44].

Footplate manipulators are bulky devices, requires large space and permanent installation to the rehabilitation room. It cannot be used in early stage of impairments as patient needs to be move to the rehabilitation centre which might be impractical in some cases.

7.1 HAPTIC WALKER

HAPTIC WALKER is the robotic device for rehabilitation used for mobility of the lower extremities. User has to stand up on the footplates while robot movers his feet by applying force-controlled trajectory during walking phases of the training session. Each footplate is designed with 3 DOFs. Working space is about; 105 degree (rotational), 0.9m (horizontal), and 0.4 (vertical). Theses footplates possess maximum velocity of 3.5 m/s. Crank rocker mechanism and linear motors are used by the hybrid kinematics for the simulation of the various walking conditions such as stair climbing, speed etc. Information about clinical examination is not available.

Medical Discipline: Rehabilitation

Function: Moves user’s legs in 3 DOFs.

Trajectory planning: offline preoperatively

Kinematics: two 3-axis hybrid kinematics setups

Kinematics type: hybrid

DOF: 3

Years of development: 2004

Developed in: Berlin, Germany

Institute: Fraunhofer IPK

Manufacturer: selfmade robot

Estimated Cost:

7.1.1 Technical Evaluation

HAPTIC WALKER includes two programmable foot plates which are permanently in contact with foot machine. System is designed for an extension of unit by unit [45]. In the sagittal plane, device has 3 DOFs per foot that are activated by basic unit. Extension of each footplate is possible up to 6 DOFs, in addition to metatarsal joint drive. Electrical direct drive motors, force/torque sensors are crucial components of the system. This system is actively and passively secured. It is safe to use for machine users (patients) or operating personnel (therapists).

FIGURE 7.1: HAPTICWALKER SETUP[45]

HAPTICWALKER is a heavy weight device. Aspects such as high passive security, easier entry for the user, and access to the user from all sides are considered during development [45]. Foot movement is achieved by linear drive motors. Motors run independently, but both are connected through a slider crank system so distal end of motors moves horizontally. Footplate module consists of footplates and 6 DOF force/torque sensors [45].

7.1.1.1 Safety

Walking simulation is used in combination with trunk suspension module in order to protect user for falling during gait rehabilitation session. At a first stage, when walking on simulator, suspension system is inactivated [45]. Later, two active drives are connected to the suspension system to enable lateral and vertical centre of mass (COM) movements in synchronization with the foot movements [45].

7.1.1.2 Control System Architecture

Two separated computers are connected through a 100Mbit Ethernet link running a TCP/IP based cyclic soft real-time communication protocol. Robotic controller is based on Linux/RTLinux. The control software is multi-robot control software which can operate different types of robots and kinematics. Synchronisation of data is achieved by using FIFO queues [45].

7.2 LLRR

Lower Limb Rehabilitation Robot (LLRR) is designed to train a patient to regain his/ her naturalised walking capabilities by exercising leg muscles and regaining neural control over the walking phases with simulation of unimpaired subject’s footsteps. LLRR helps patient to recover his/ her walking functions gradually [46].

7.2.1 Technical Evaluation

LLRR is based on the concept of constructional divergence in development of mechanism of rehabilitative robotic devices. This divergence states, in general there are two types of mechanisms [46]: Complicated and uncomplicated. Complex mechanism can simulate all sort of walking phases completely as it is composed of complicated and a large number of mechanical parts. On the other hand, uncomplicated structure can generate restricted walking phases. Instead of assisting totally to the user for walking, uncomplicated structure can support and motivate patient to walk. As it is adaptive for user, he / she can receive rehabilitation training from LLRR [46]. In addition, reliable and simple properties of uncomplicated structure are beneficial for design and control strategies.

7.2.1.1 Mechanism and Structure of LLRR:

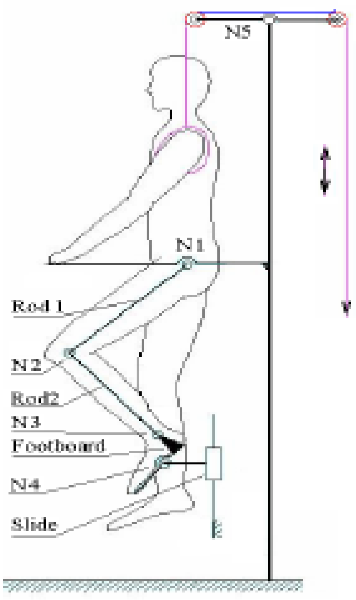


FIGURE 7.2: STRUCTURE OF LLRR [46]

Right and left legs can be driven vertically up and down by the body weight alleviated parts alternatively and respectively. This process can also be considered as a cause to the resultant of forces such as ball circulating screw and nut, DC servomotor, bearing inside the driving unit and reduction gears.

Legs assisted parts simulates desired trajectories and regulates the walking gestures. There are two rods and two footplates symmetrical to each other. Duplicate pairs of legs assisted parts for left and right side are combined with two rods (rod 1 and rod 2 each for left and right side) platforms in correlation. One more advantageous feature of LLRR is, footplates enforce the embedded array to stimulate the feet acupuncture points which is beneficial for the lower limb rehabilitation.

Functioning of balance keeping parts and body weight alleviating parts are based on classical lever principle. Function of the lever is to divert part of body weight to sling cable, load burdens, lever, suspenders and pulleys.

These main parts are bunched up together and connected to a main frame. Figure 7.3 shows the orthogonal isometric projection of Lower Limb Rehabilitation Robot.

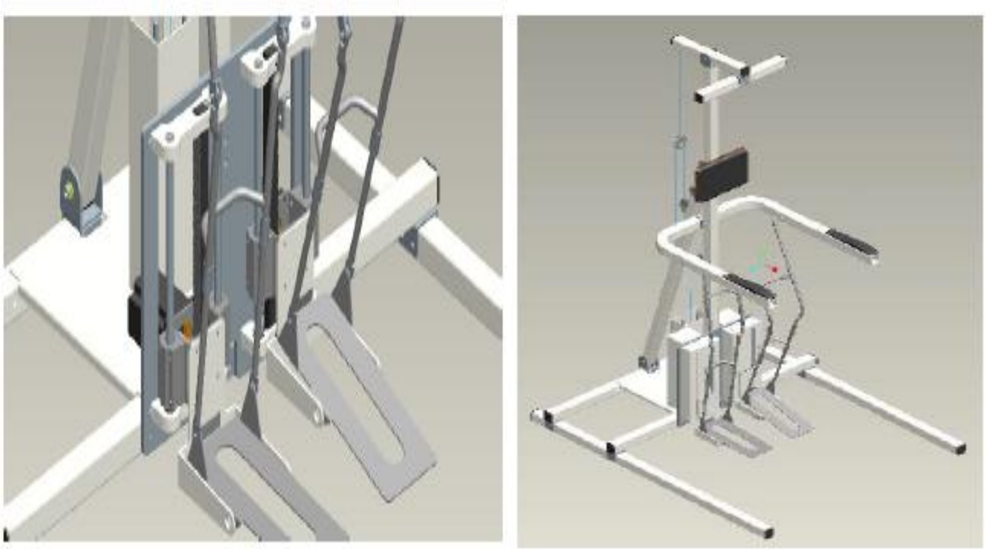


FIGURE 7.3: LEFT PICTURE SHOWS LEG-ASSIST AND DRIVER PART. RIGHT PICTURE ILLUSTRATING ORTHOGONAL ISOMETRIC PROJECTION OF LLRR [46]

7.2.1.2 Control System Structure of LLRR:

There are four modules of control system structure:

- Weight alleviated and balance keeping control subsystem
- Time measuring control subsystem of the left and right legs
- Micro motor control subsystem of the foot acupuncture point array
- Control system of the robot

First three modules are driven by the DC servomotor (rating power 250W and rotating speed 2000 r/min for each set); they might work at a lower speed as well. AC servomotors or brushless moment servomotors can serve the control drivers in rehabilitation training as stepping motor and DC electric engine are unable to fulfil the demand to drive all three modes; Displacement control, Velocity control, Moment Control.

Control system comprises a set of PC to control and control card along with a control program [46]. Using the pulse/direction instruction, DC motors control the current in the motor coil so that it can control the movement direction and speed of pedals.

LLRR offers to use robot for two training modes of rehabilitation.

Passive movement training mode: Motors adapts velocity control mode through programmable control card. It set the new target value of the movement speed and maximise the assistance moment. It is suitable for totally ill patients.

Assistant movement training mode: it is suitable for patients with limited movement functionality. Motors adapts moment control mode using programmable control card and set the range of speed.

Authors of LLRR have concentrated on the improvement of sensing techniques to sense the status of impaired limbs. Immediate estimation of muscle tension and effective response to the control system can prevent the hazardous and unpredictable situation that might emerge during rehabilitation such as tearing of muscles, injuring the ligaments, muscle spam etc.

CHAPTER 8: STATIONARY ROBOTIC GAIT TRAINER

Stationary robotic gait trainer devices are designed to guide paretic limb to perform movements in early stages of injury to achieve therapeutic and functional progress [47]. Similar to other robotic techniques, objectives of stationary robotic devices are; muscle strengthening, balance and stability in motion and joint mobility [47]. Difference is these devices provide horizontal support such as a bed or chair for the user's body (upper limb) instead of vertical displacement.

It has been proven that rehabilitation training must be provided to the patient as early as possible after the injury. Longer time span reduces the chances to regain normal walking abilities. If a patient could not receive rehabilitation in appropriate time, that may lead to secondary complications due to immobility [48]. So, that emphasise the importance of rehabilitation in early stages of stroke or injury, recovery from major surgeries.

Not all patients can move to the rehabilitation centres for training due to medical complications. All other robotic devices cannot be useful in such cases as they require large space and permanent installation in the rehabilitation centre. Stationary robotic devices are comparatively smaller and portable. These devices can be easily move, and devices such as RRH1 can provide rehabilitation on the user's bed itself. These devices are effective for primary stages of rehabilitation, after a necessary improvement in patient's physical condition; he/ she can be moved to the rehabilitation centre for further training.

8.1 MOTIONMAKER™

8.1.1 Technical Analysis

The MotionMaker™ is the first device from the rehabilitation program of Swiss foundation for Cyberthoses. During early stages of recovery such as just after surgical operation, this device can be used for rehabilitation. After gaining sufficient recovery, patient can be treated with 'Walktrainer' for further rehabilitation.

MotionMaker™ is a stationary programmable test and training system that uses closed-loop electrical stimulation to provide rehabilitation of lower limbs to patients suffering from spinal cord injury and hemiplegic patients [49].

FIGURE 8.1: PROTOTYPE DEVICE [49]

Basic concept of MotionMaker™ is based on the necessity of functional electric stimulation during the recovery period. Medical complications may take place following the paralysis resulted from spinal cord injury. During this period patients may not be able to join rehabilitation program. Time taken during this phase may affect badly to the total rehabilitation program in later stage. So it is important to maintain a patient’s muscular activities with functional electric stimulation. FES must stimulate muscle with the sequence of muscle contractions in order to maintain muscular activities [49]. If FES is combined with the orthosis, this hybrid orthosis can serve as a rehabilitative device [49].

MotionMaker™ is a Cyberorthsis (contraction of cybernetic and orthosis), combination of closed-loop electrical muscle stimulation (CLEMS) and orthosis. It is enable to produce progressive and active muscle participation [49].

8.1.1.1 Construction and Mechanism

MotionMaker™ is composed of 3 DOF. It is designed using two orthosis; a motor with real time regulation, a multi- channel electro stimulator and a worktable; as well as a control unit managing the electrical stimulation [49]. Picture of the first developed MotionMaker™ is shown in figure 8.2. This configuration helps paralysed patient to perform leg movements with specific and predefined characteristics such as speed, position and torque [49].

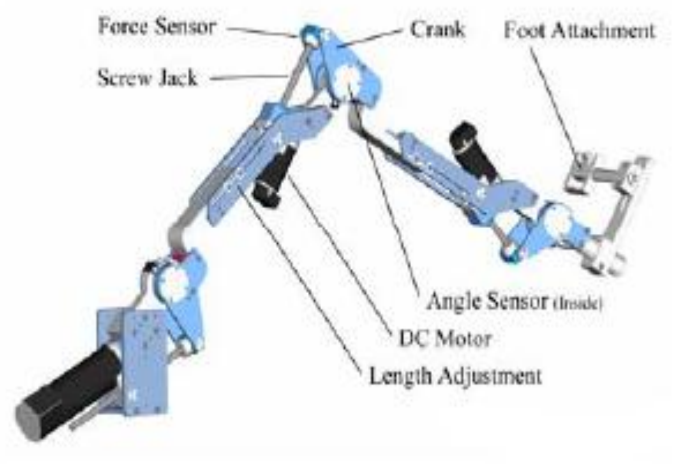


FIGURE 8.2: LEG ORTHOSIS [49]

MotionMaker™ is designed considering patients with the height from 150 to 190 cm. Foam mattresses are used to provide comfort. Inside the frame, control unit and the electro stimulator are attached [49].

Orthosis is to be placed on the external side of the leg. It has three joints for hip, knee and ankle. Screw jack activates the crank system. DC motors drive the screw jack mechanism. This orthosis moves only in the sagittal plane being a pin axis [49]. Length of the leg segment can be manually adjusted [49]. Worktable provides a comfortable and effective position to the patient for exercise. In a current version, all adjustments of DOF have to be done manually [49].

8.1.1.2 Control System

The control system of the MotionMaker™ includes an intelligent central unit, industrial PC with a real time extension with axis interface board and amplifiers [49]. Control architecture is a combination of electro stimulation and motion control. This flexible control system includes several different modules. Some of these modules work in real time processes using the real time controller [49].

FES control ensures frequency and optimal stimulation with consistent pulse width of 300 µs [49]. Different types of electrodes are attached to the both limbs on principal muscles such as vastus Lateralis (VL), Hamstring(H), Gluteus Maximus (GM), Rectus femoris (RF), Tibialis Anterior (TA), Vastus Medialis and Gastrocnemius [49].

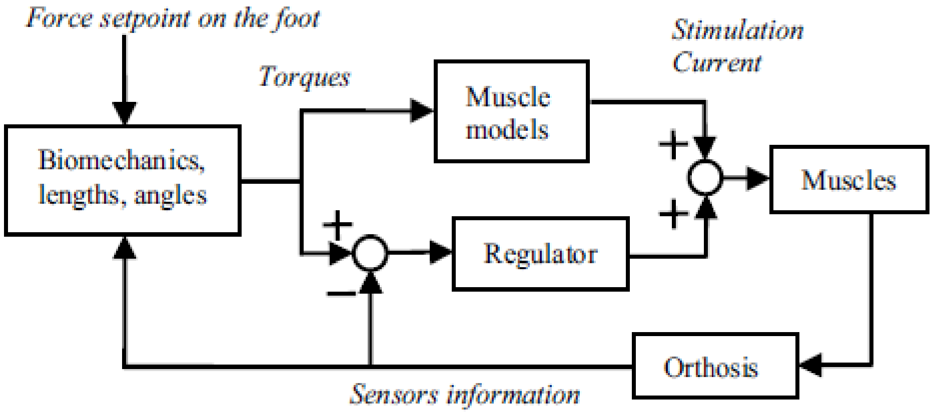


FIGURE 8.3: FUNCTIONAL ELECTRICAL STIMULATION CONTROL SYSTEM [49]

Figure 8.3 above is a schematic representation of functional electrical stimulation control scheme. This control model is based on feed-forward and conventional regulator [48].

Cyberorthosis system has overcome with two basic limitations of FES capacity; to control the contraction of the various muscles with FES and a rapid muscle fatigue [49].

8.1.2 Clinical Evaluation

Primary tests were performed with MotionMaker™ to ensure its feasibility of FES with a closed-loop control of muscle activation. Stimulus was given to the gluteus maximus and the quadriceps of healthy patient [48]. Generated torque pattern was measured. Torques setpoints and measured torques were compared. Measured torque was almost similar to the torque set point. Positive results of this test confirmed feasibility of the MotionMaker™ [48].

After few primary tests and some modifications to enhance safety as well as to assist the therapist’s work; clinical experiments were conducted with SCI patients.

5 SCI patients (4 with an incomplete SCI and 1 with complete SCI) had gone through two months MotionMaker™ training programme. MotionMaker™ training was absolutely comfortable for every patient; none of them dropped out or felt pain. Device was safe especially because of spam management; no musculoskeletal incident was recorded. Spasticity was also studied. 3 patents had shown hypertonia, but after the training of one hour, hypertonia decreases by 0 to 1 level, almost abnormal level. Patients with incomplete SCI could develop more voluntary strengths with electrical stimulation and an increased awareness for muscle activity. That means larger sensory input given to the neuronal circuits might facilitate voluntary motor activity. After the training of one and half month, 3 incomplete SCI patients could develop a voluntary force (< 150N) without electrical stimulation that was not possible before training.

In aforementioned case studies, feasibility and usefulness of use of MotionMaker™ for SCI patients is proved, but detailed analysis is still required. Author has not mentioned about results with complete SCI patient and other incomplete SCI patient. Detailed analytical data about set point acquisition, its implementation and effects on the individual subjects need to be investigated. To ensure benefits form use of MotionMaker™ to provide rehabilitation to patients suffering from central nervous system injury, further experiments are required. Besides clinical experiences, MotionMaker™ can be economically feasible. Only one therapist can assist two patients at a time [50]. Comfort, no need of special room, easy to transport make it more efficient to use.

8.2 LAMBDA

8.2.1 Technical Evaluation

Concept of parallel robot is used for the rehabilitation and fitness robotics for lower limb. Lambda is a robotic device designed with 3 DOF for rehabilitation for lower limb in early stages of the recovery such as patients out of coma or major surgical complications. This device is called Lambda because this orthosis looks like a Greek later lambda (λ) [51].

Parallel kinematics has been used for Lambda that is based simplicity of design and stiffness. Structure is based on two translational articulations. To carry out the ankle motions, one rotational motor is used. Lambda robot offers mobilisation of lower limb in the sagittal plane inclusive of additional rotation. Overall structure provides effective movements for hip, knee and ankle in order to serve the purpose of rehabilitation, sport training or fitness.

8.2.1.1 Construction and Mechanism

Construction of Lambda is based on four parts: The Lambda structure, the base, the seat and the ankle mobilisation structure. Whole structure is consisted of 3 active joints and 3 passive pivots. As shown in the figure 8.4, two translational articulations (around Y axis) and one rotational joint (around P axis) make the mobilisation possible. 2 motors among 3 motors used in Lambda are on the frame for translation, and another one is placed on the lambda structure (moving with it). This motor actuates ankle motion.

The Base: Base provides a platform for several components to be attached with. Cable hangers, motors, screw fixation, linear rails and drives from motor are mounted on the base. Linear actuation of A and B axes are carried out by these components. Cable hangers also help to actuate P axis.

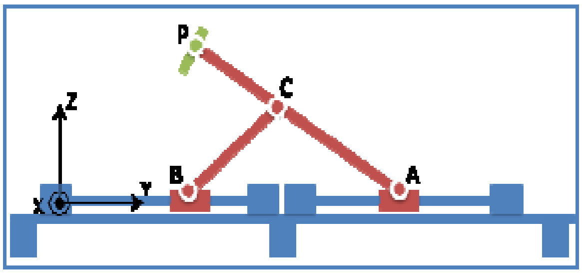


FIGURE 8.4: SCHEMATIC REPRESENTATION OF LAMBDA BASE [51]

The Lambda Structure**:** As shown in the figure 8.5, structure can be divided into AP and AB sections. AP section is manufactured by using riveted folded aluminium plates. A-pivot has 2 ball bearings. Carriage acts as a linear slider between the AP section and the base. A screw/ ball nut system actuates the AP section. This configuration provides high stiffness. C-pivot, made up of two parallel bars and perpendicular rod is mounted in the middle of AP section. C-pivots link AP and AB sections. AB section links the Lambda structure to the base.

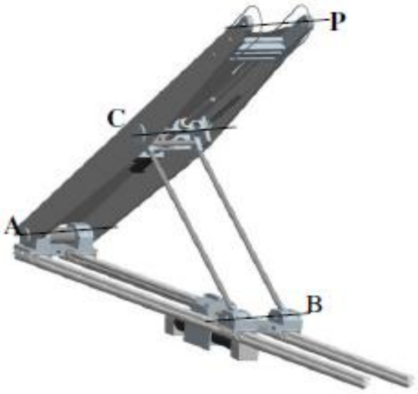


FIGURE 8.5: SCHEMATIC REPRRESENTATION OF LAMBDA STRUCTURE [51]

The ankle mobilisation structure: Figure 8.6 represents the ankle mobilisation structure, The ankle mobilisation structure is placed on the P axis of the AP section where pivot joint allows rotation around P axis. This structure is also activated by screw/ ball nut system. Driver motor moves with AP section. Cables are linked to ball nut. So cables follow the same direction in which ball nut move. Movement of cable actuates the ankle mobilisation structure.

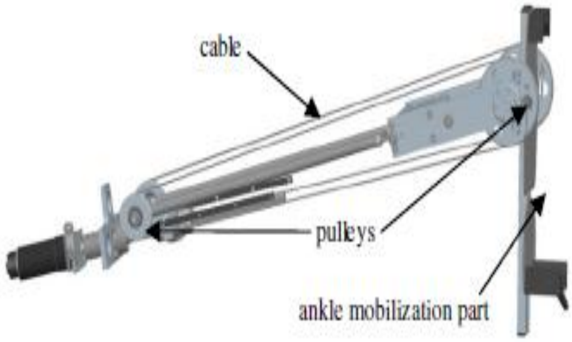


FIGURE 8.6: THE ANKLE MOBILISATION STRUCTURE [51]

The seat: Seat allows a patient to be placed in position according to Lambda structure. Seat allows one rotation of the back and two translations in the sagittal plane.

FIGURE 8.7: SEAT OF LAMBDA [51]

8.2.1.2 Control System

Control system of Lambda is composed of three controllers: Standard positioning PID controller, PID controller integrated with static model compensation and PID controller integrated with a dynamic model of the robot. No detailed information on control scheme of LAMBDA is available yet.

8.2.1.3 Safety

Security strategy for the Lambda has been implemented in four stages.

1. Error based failure: Identifies position control loop errors (velocity errors, position error etc.)
2. Workspace based failure: Checks the targeted and measured variables in correspondence with their own workspaces (absolute and differential).
3. Redundancy based failure: This level observes consistency of the redundant variables and makes sure that differences are acceptable.
4. Hardware based failure: This level is for hardware of the system. If any abnormal signal appears, this level raises the failure signal that stops entire control system.

LAMBDA prototype device is under research yet. Clinical evaluation has not been done. So, it is difficult to draw a firm conclusion about its effectiveness and possible user group who may benefit from it. Roughly we can

8.3 RRH1

Technical University of Łódź (TUL) has developed a rehabilitation robot for lower extremities. RRH1 is specially designed to allow rehabilitation treatment to the patient in early stages of coma or injury. Patient can perform exercise just lying in their bed. RRH1 provides two-plane motion exercise simultaneously, for the knee and for the hip.

8.3.1 Technical Evaluation

8.3.1.1 Construction

Construction of RRH1 is as shown in figure 8.8. It is made up of two rigid arms connected to the patient through harnesses bonded with the patient’s ankle and knee, an adjustable column based on the wheeled platform that robotic system to relocate and adjust itself for the perfect position to provide therapy for the bedridden and or unconscious person. Main components of RRH1 are driving system and robot arm.

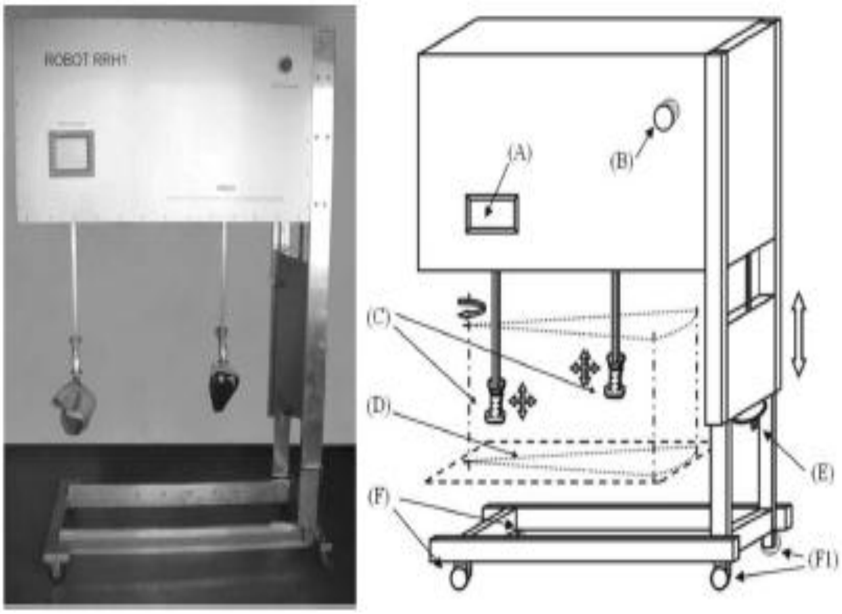


FIGURE 8.8: PROTOTYPE DEVICE [52]

Lightweight construction of RRH1 (near about 100 kg) includes adjustable column placed on the rectangular base, aluminium chassis and two standard wheels along with two castor wheels for easy movement of the whole mechanism from one bed to another bed in hospital or for fine placement at bedside. This mechanism eliminates the need of relocation of a patient to the rehabilitation area. After placing a device in the exact position, breaks mounted on the wheels can lock the device. Crank makes height adjustable for a particular patient and bed.

8.3.1.2 Kinematic Structure

Kinematic structure of the RRH1 is as shown in figure 8.9. It is based on the cylindrical scheme having 5 degrees of freedom. Driving system is same for all joints of the robotic device: DC motor with incremental encoder and reduction gear head, electromagnetic clutch and rotary potentiometer for accurate measurement of joint's position [52].

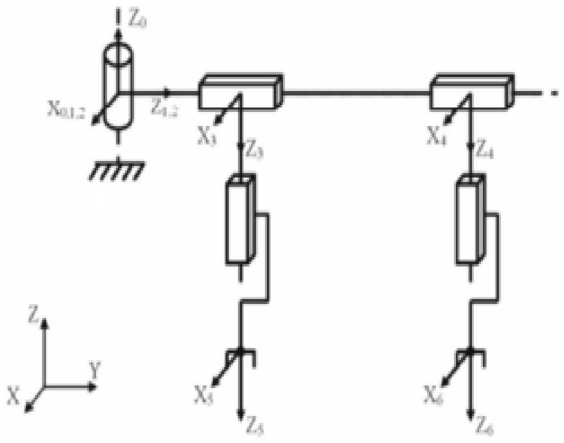


FIGURE 8.9: KINEMATIC STRUCTURE [52]

A special toothed guide having two carriages traveling on it is inside the chassis. Each carriage is consisted of two drives; One who drives carriage in the horizontal direction and the other one for motorizing vertical alarm [52]. These drives are connected to the both arms in mutually perpendicular fashion where arm 1 is responsible for holding knee, and arm 2 holds foot. Both arms generate extension and flexion movements for exercise of knee and hip. Main toothed guide rotates around Z axis, and this extra DOF is responsible for the expansion of functionality of the rehabilitation robot [52]. This DOF adds adduction and abduction movements for the exercise of hip as shown in figure 8.10.

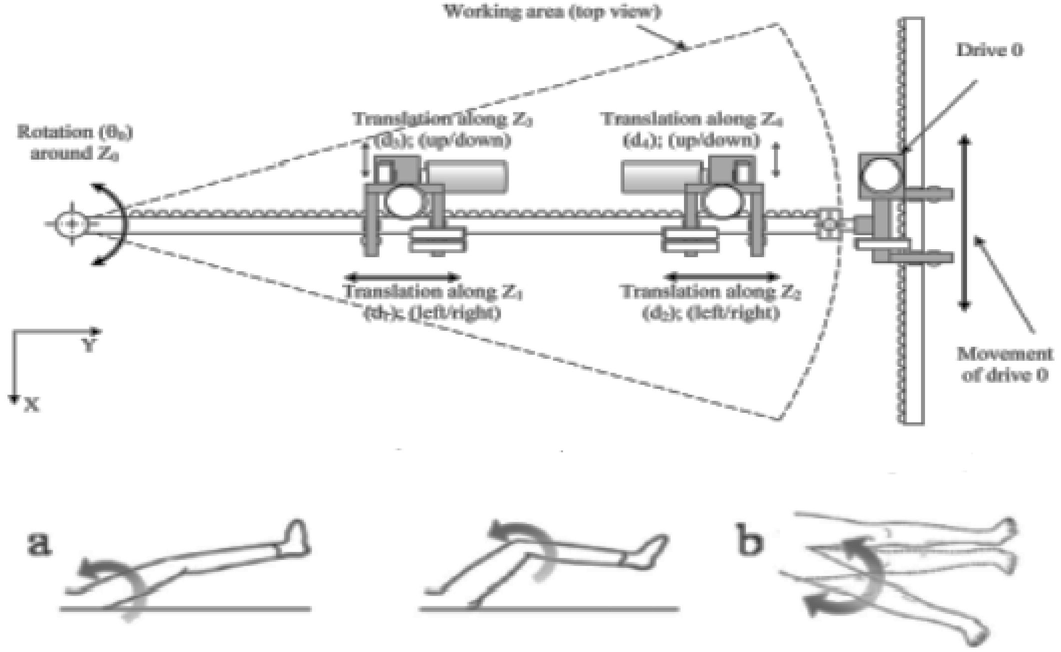


FIGURE 8.10: INTERNAL STRUCTURE OF DRIVING MECHANISM AND EXERCISE GENERATED BY RRH1[52]

8.3.1.3 Structure of the Control System

Control system of RRH1 is based on the concept of Distributed control system (DCS). DCS collaborates with Human Machine Interface (HMI). Through a CAN bus, main controller communicates with local controllers. Main components of control systems are: The main controller, The Human-Machine Interface, The local controller [53].

The main controller: It is based on AT90CAN128, 8-bit single-chip microcontroller from Atmel. It is equipped with SRAM memory to store trajectories recorded during a training session. The CAN bus is the integral part of the controller. Controller also has USB port and monitoring external PC. The controller transmits information about motor torque, the position and emergency events during rehabilitation training process [53].

The Human-Machine Interface: HMI helps therapist to communicate with a device. It has LCD graphic display to display all information about emergency events, error occurred during operation, current status etc., and resistive touch pad layer on the entire screen [53].

The local controller: It is based on the miControl® Digital Servo Amplifier (DSA) that uses a hall sensor or an incremental encoder for position and velocity feedback. A trapezoid velocity profile can be generated. It can also work in velocity, current (torque) or position mode [53]. DC motors are directly driven by a local controller uses position feedback from the potentiometer and incremental encoder, control the electromagnetic clutches as well as measure the motor current [53].

8.3.1.4 Safety System

- When emergency stop button is pressed it cuts off the power for motors immediately [53].
- In any phase of the teach-execution algorithm, software stop executed on the touch panel [53].
- System monitors the velocity, position and force of each joint continuously. If any distortion/ disturbance or error appears, device stops working [53].
- If malfunctioning of the communication layer appears device stops working [53].

RRH1 is recently developed design that was proposed in 2010. It is being prepared for clinical studies. So no data is available on clinical experience yet.

CHAPTER 9: OVERGROUND GAIT TRAINER

Past studies proved that there is a difference between treadmill walking and over ground walking. Satisfactory performance on treadmill training cannot be the same on overground. Speed can be decrease stability and balance can get affected specially at low speed of walking. As a solution to this problem, concept of overground gait trainers was proposed.

Unlike the other devices such as BWS treadmill gait trainer; overground robotic devices allow intense access to the physiotherapist. In other devices, physiotherapist cannot interact with patient. Here, physiotherapist is allowed to fix misalignment if any as well as to provide task specific training. This configuration also eliminated the risk of sliding of robotics joints attached to the human joints.

Overground gait trainers are human interactive devices that provide partial body support to user. Basic components are frame to accommodate whole mechanism of the device and harness to supports the body weight of user.

9.1 WALKTRAINER

The WalkTrainer is a robotic system for rehabilitation made up of a de-ambulator, a body weight support, a pelvis orthosis, a real time controlled electro-stimulator and a two leg orthosis that allows rehabilitation for paraplegic or hemiplegic patients. This device was developed by the “Laboratoire des Systemes Robotiques (LSRO)” at “Ecole Polytechnique Fédérale de Lausanne (EPFL)”.

9.1.1 Technical Evaluation

9.1.1.1 Concept

Conceptual diagram of WalkTrainer is as shown in figure 9.1. Successful experimental results of Motionmaker were the inspiration behind the WalkTrainer where a de-ambulator is connected to the vertical fashioned orthosis. WalkTrainer is an over-ground walking rehabilitation system.

9.1.1.2 Construction and Mechanism

Device is composed of five main parts those are bounded with user by two-way communication. Mechanical parts are de-ambulator, pelvis orthosis, leg orthosis and body weight support. Electrical part is a closed loop electrical muscle stimulation.

De-ambulator: Main frame carries all sub-components and controllers as well as that follows the user during the training session. Two motorized wheels are mounted on the frame in differential way that allows a rotation around the vertical axis and movement along the forward axis.

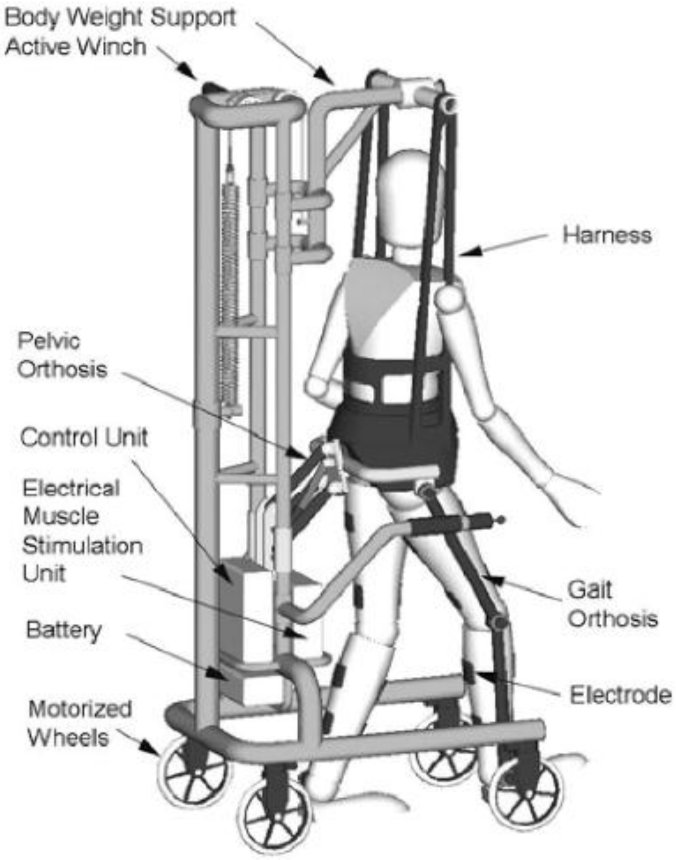


Figure 9.1**: Schematic diagram of walktrainer [54]**

The Body weight support: Functions of the body weight support systems are to unload the user by applying controlled force and to prevent him from falling down.

Pelvis orthosis: Function of the pelvis orthosis is to assist the user during walking as physiotherapist supports. Parallel kinematic structure is shown in figure 9.2. A force sensor and DC motor are placed on the each axis of the orthosis.

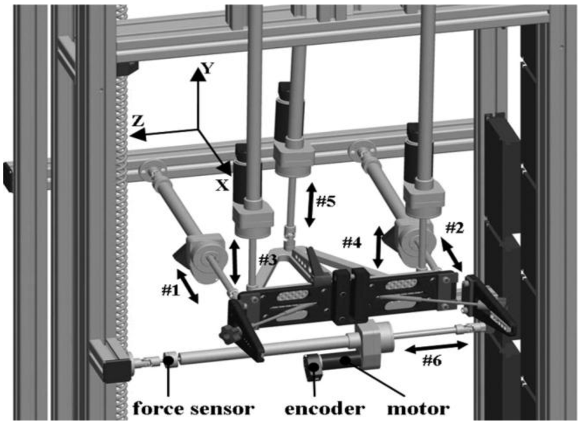


FIGURE 9.2:PELVIS ORTHOSIS

Leg Orthosis: Leg orthosis performs two primary functions; measures and guide positions of the user’s leg (ankle, knee and hip) as well as it monitors the interactive forces between the user and itself. For this reason, leg orthosis is attached with the force sensors and motors. All gathered information regarding a position and force will be utilised for the closed loop muscle stimulation as shown in figure 9.3.

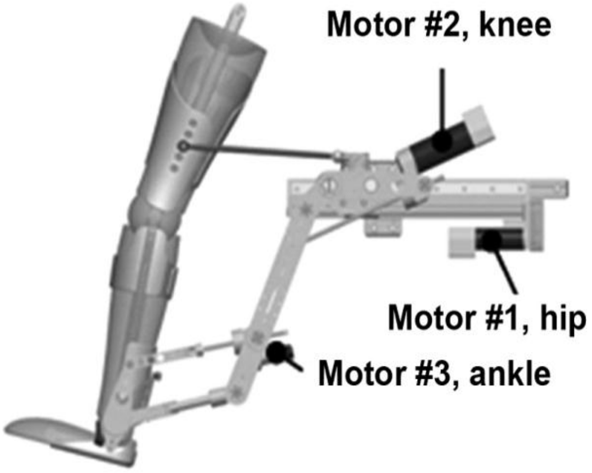


FIGURE 9.3: LEG ORTHOSIS

The Electro-stimulator: WalkTrainer system uses a real time twenty channel electro-stimulator. It is used to stimulate following muscles: Gluteus Maximus, rectus femoris, biceps femoris, tibialis anterior, vastus lateralis & medialis and gastrocnemius.

9.1.1.3 Control Architecture

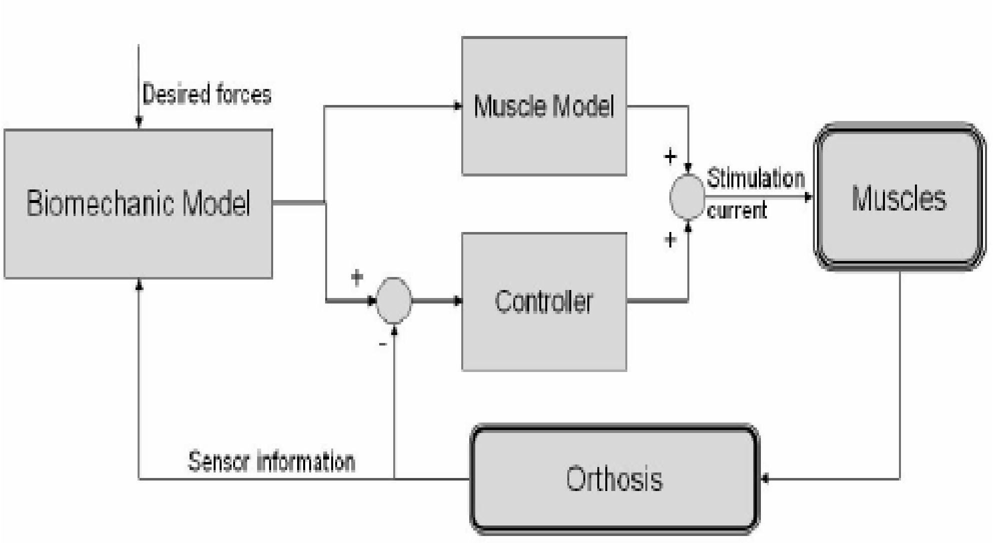


FIGURE 9.4: FUNCTIONAL BLOCK DIAGRAM OF WALKTRAINER [54]

Control system of the WalkTrainer is based on the two control layers including Windows PC based controller with a real-time extension. The real time layer executes all deterministic events and real time processes. The application functionalities of the set up and execution are implemented by the Win32. Graphical interface allows communication with a machine.

With setting the behaviour of Master component, co-ordination with other different parts can be achieved. By using appropriate control strategies, it adapts the function of other sub-devices. As Leg Orthosis maintains the interaction with the user, Authors have chosen Leg orthosis as a Master component. This master component interacts directly with the user and records all the articular coordinates of the leg.

9.1.1.4 Control Strategy

Design of pelvis orthosis comprises 6 DOF measurements that carried out in real time. It includes foot switches, Two potentiometer (distance sensors) and 6 DOF optical tracking device. Potentiometers measure the relative distance and speed between the user and the device. These sensors also correct the heading of ambulatory if the user is not walking on desired trajectories (in straight line).

In a control cycle, first, encoders and potentiometers use the speed of the user. When user is walking at a constant speed, filtering process permits a fast reaction (as per requirement) and a smooth averaging. At later stage, the differential motion of distance sensors gives orientation so that guiding the de-ambulator is possible in order to keep it behind the user. This can prevent drifting. Speed adaption algorithm for pelvic motion measurement is shown in figure 9.4.

9.1.1.5 Safety

Hardware: WalkTrainer system has been designed with doubled critical sensors. It is also equipped with security card that can detect abnormal response from sensors, crash of the PC or any erroneous situation and directly controls to the motors and power drives. System also includes several emergency stop buttons [54].

Software: Abnormal functioning of sensors, errors in control system or trajectory generation can affect directly to the motors. Appropriate use of the software reduces this risk as well as secures all mechanical interfaces too. This project is a new approach in the rehabilitation training process. Combination of closed loop electro-stimulation and motion is advantageous as it:

- It improves muscle behaviour
- It improves voluntary muscle control
- It improves coordination in walking process
- Improves joint mobility
- Reduces osteoporosis risks
- Improves blood circulation

9.1.2 Clinical experiments

Wide ranges of clinical experiment have not been performed yet. Apart from evaluation and feasibility experiments conducted in 2005, only other experiment was conducted in 2008 according to available data. As per the study conducted in 2008, six paraplegic subjects participated in clinical trials with WalkTrainer. During these three months training no patient was dropped out [55]. That confirmed that device provided comfort.

Study confirmed orthosis and muscle stimulation feasibility of WalkTrainer in paraplegic patients too [55]. Reduction in spasticity was also observed. However, training rate, one session per week was too slow to demonstrate any significant improvement in force or coordination [55]. Further investigation is needed to explore more benefits of the device.

9.2 MOONWALKER

MoonWalker is a quasi-passive (requiring very low energy) lower limb exoskeleton that can sustain a wearer’s bodyweight with the use of gravity force balancer. MoonWalker provides rehabilitation for patients having weak legs or with a broken leg. It also provides assistance to carry heavy loads; especially for military purposes. It can assist in climbing up or down stairs or slopes.

FIGURE 9.5: MOONWALKER [56]

9.2.1 Technical Evaluation

9.2.1.1 Design Concept

Basic idea behind the development of MoonWalk was to lighten the forces in user's legs by applying an upward vertical force on the pelvis [56]. MoonWalker makes user's leg to feel only a part of body weight, giving him/ her feeling of walking on the moon where gravity is reduced. Another important concept of MoonWalker was to offer assistance on flat ground as a passive device which can act as a gravitational potential energy. This concept is elaborated in the figure 9.6. As shown, user is connected to the trolley through a force balancer that applies constant vertical force on the pelvis that lighten the forces due to his bodyweight on his legs. A force balancer placed between the user's pelvis and the trolley allows vertical motion.

In actual design of MoonWalker, this trolley is replaced by two sticks, each attached to the each leg. This design makes devise an exoskeleton. Bodyweight compensation concept with two poles is demonstrated in figure 9.6.

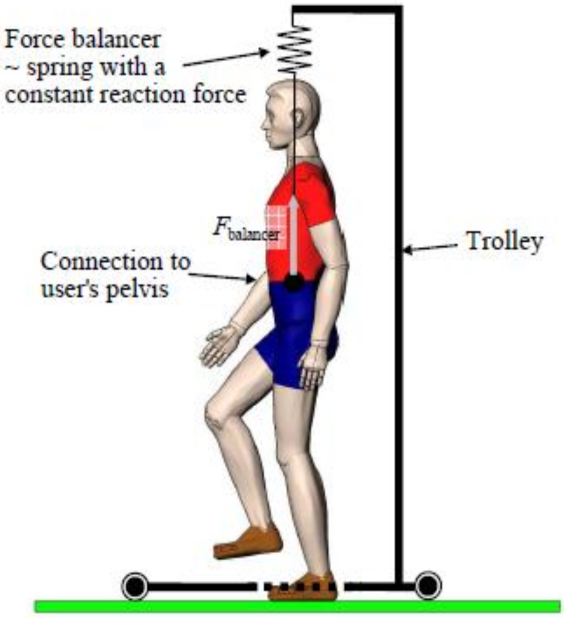


FIGURE 9.6: BODY WEIGHT COMPENSATION RINCIPLE ILLUSTRATED WITH A TROLLEY EQUIPED WITH A FORCE BALANCER [56]

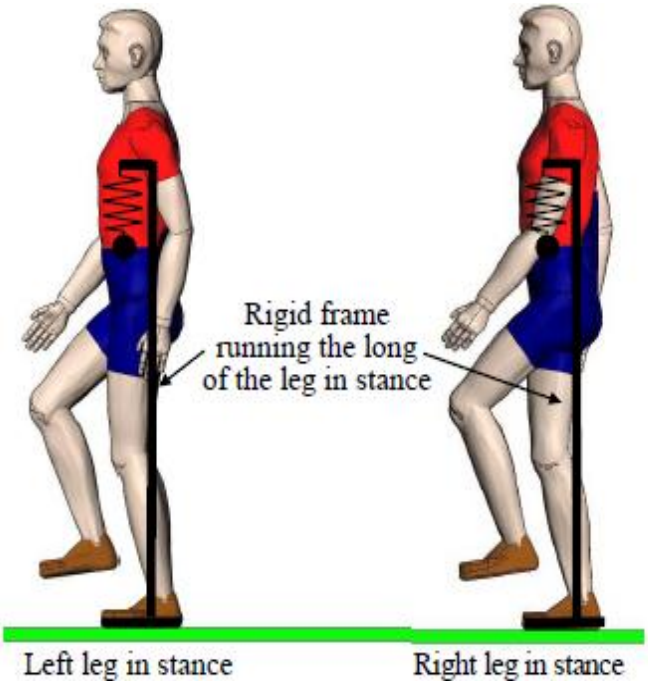


FIGURE 9.7: BODYWEIGHT COMPENSATION PRINCIPLE WITH TWO POLES RUNNING ALONG EACH LEG [56]

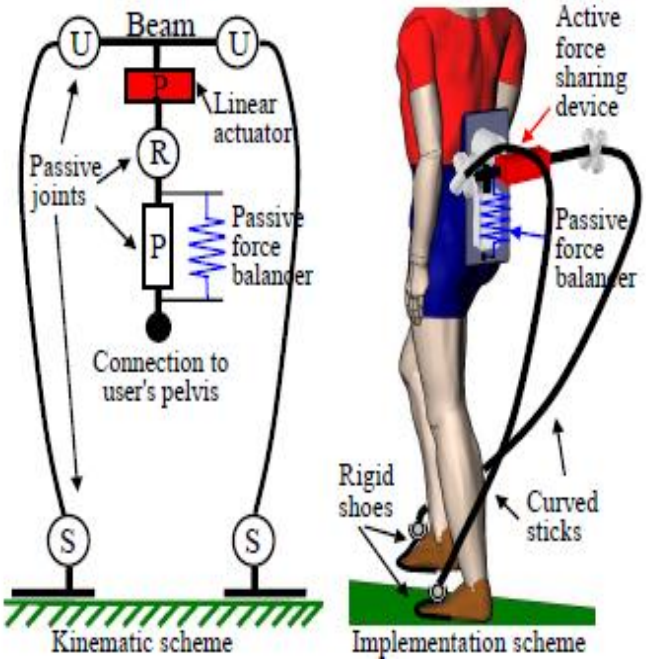


FIGURE 9.8: KINEMATICS AND IMPLEMENTATION SCHEMES OF MOONWALKER [56]

9.2.1.2 Force sharing device

The balancer between the two sticks exerts the force. The force sharing device shares this force in a continuous manner. This mechanism is as represented in the figure 9.7.

The force sharing device includes a beam. Passive universal joints (U) connect end of the two sticks to the beam. An actuated prismatic joint (P) makes the beam slide left or right. A passive revolute joint (R) is attached with the linear actuator as shown in the figure above. This vertical cart is connected to the force balancer. Using spherical joints (S) the sticks those are attached to the rigid shoes, transmits the forces passing through them to the ground. Thus, U and S joints are placed at the end of the sticks to transmit the balancer forces to the ground so that shoes can move freely.

Figure 9.9 shows the two different positions of walking. During standing position, the balancer force is equally distributed over the legs by the centred beam. In second case, beam is shifted to the right as right leg is in swing and left leg is in stance. When beam is at the right side, force balancer does not apply force on the right side which make free movements of right leg possible. Force balancer exerts force on the left stick which is then transmitted to the ground. In another walking position, when right leg is in stance opposite configuration of force balancer applies.

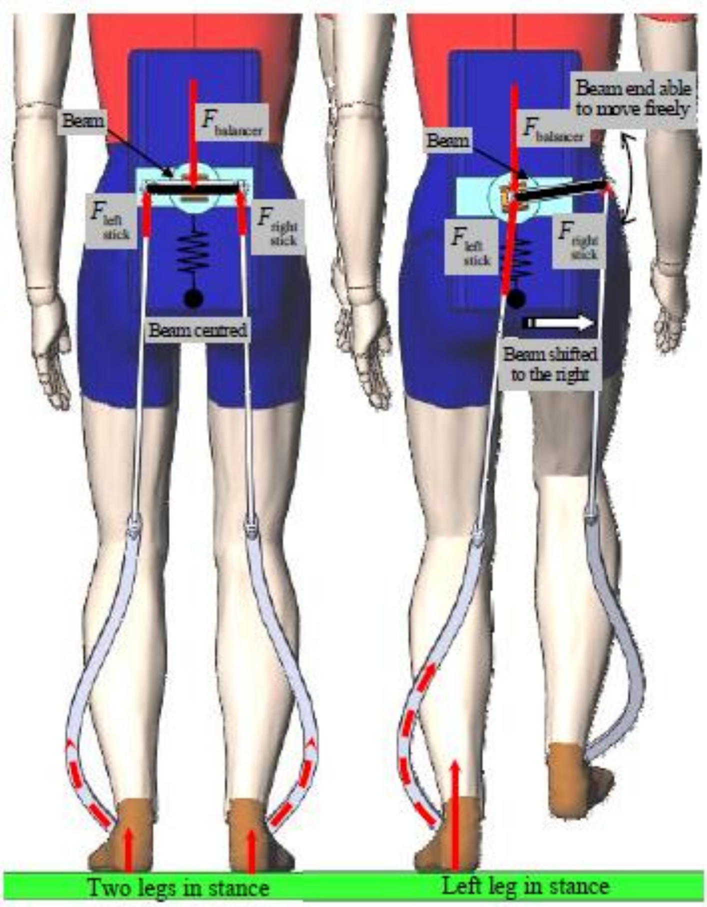


FIGURE 9.9: FORCE SHARING DEVICE FOR TWO DIFFERENT CONFIGURATIONS [56]

9.2.1.3 Control System

Control system of MoonWalker is based on the concept that measures the reaction forces shared by user on the ground and control the force sharing device in order to balance two sticks by distributing balancing force in required proportion as per demand. Pressure sensors are mounted beneath the user's feet. MoonWalker is equipped with three pressure sensors; two of them are placed on the front of shoe and one is placed under the heel. These sensors measure the pattern of the reaction forces shared by user. Displacement of the main beam can be achieved by actuator and controlling the actuator force sharing device can be drive. So, force sharing device can control the movement of the main beam with controlled actuator. Control scheme is as shown in figure 9.10.

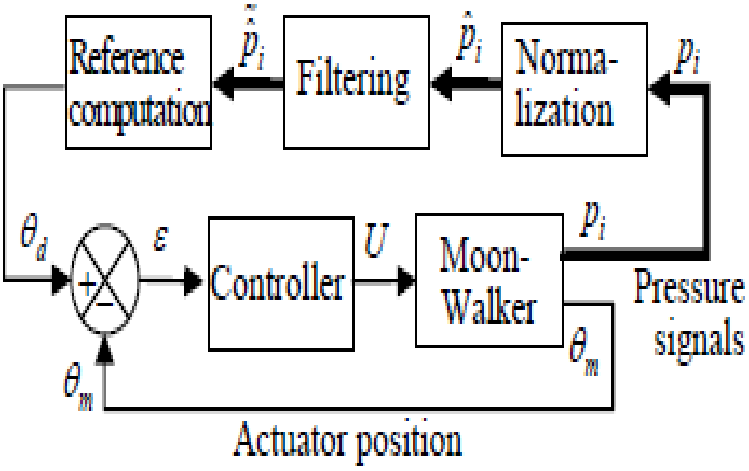


FIGURE 9.10: CONTROL SCHEME OF MOONWALKER **[56]**

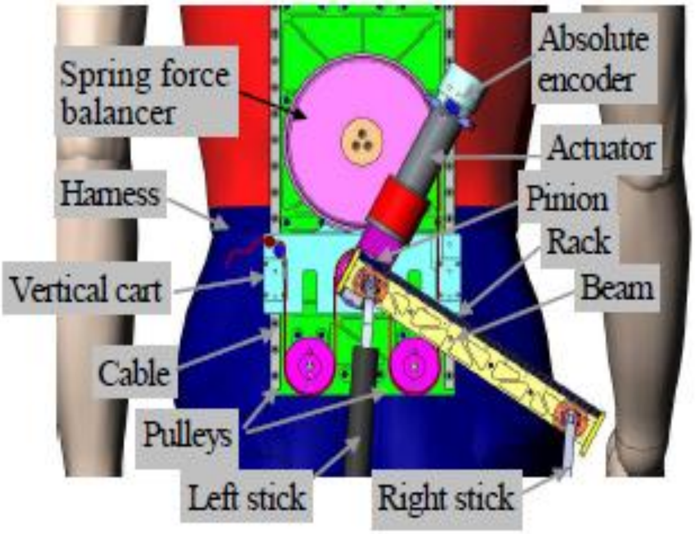


FIGURE 9.11: CAD VIEW OF PRACTICAL IMPLEMENTATION OF FORCE SHARING DEVICE [56]

Figure 9.11 shows the practical implementation of the force sharing device. Important feature of MoonWalker is, it uses passive force balancer that provides the force to sustain a body-weight. Moreover, MoonWalker consumes very low energy as it uses actuators to control force balancer. For task that needs extra energy such as climbing the stairs or slope, device uses motors. This approach might improve energetic anatomy of lower limb exoskeletons.

9.2.2 Clinical Experiments

As MoonWalker is one of the recent developments in rehabilitation robotic field, no detailed and confirmed clinical experiments have been performed yet. Early experiments performed with healthy subjects have demonstrated effectiveness of this proposed concept. Subject did not feel pain or uneasiness during training [56]. Assistance provided by the device was satisfactory even in semi-crouching positions and walking upstairs [56].

9.3 KINEASSIST

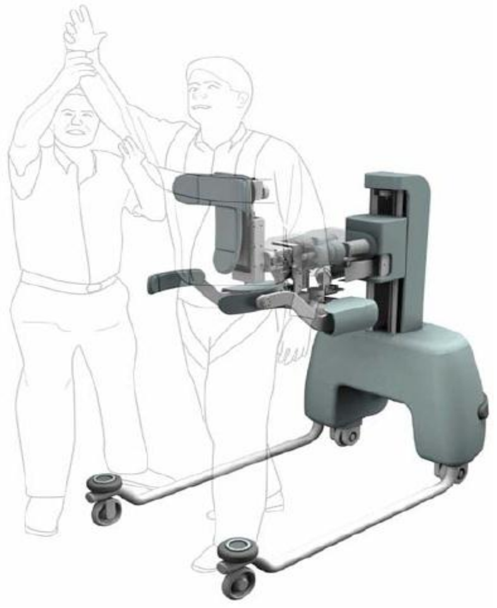


FIGURE 9.12: CONCEPT OF MOONWALKER [57]

KineAssist is an overground gait and balance robotic device for rehabilitation. Conception behind development of the KineAssist was the need to provide gait training, maintaining balance of patients overground. For physiotherapist, there are hurdle such as, he may have to provide safety to person three times larger than himself. So that created a necessity of robotic device with human-interactive robotics techniques that can provide gait and balance training overground assuring the safety while maintaining the direct involvement of physiotherapist.

9.3.1 Technical Evaluation

KineAssist is based on partial weight support technique that offers a postural torques to the human trunk. Device supports the motion of the trunk and pelvis keeping legs accessible to the physiotherapist. Device follows walking motion of the patient overground and prevents him/ her from falling.

9.3.1.1 Construction, Mechanism and Control Scheme:

FIGURE 9.13: PROTOTYPE DEVICE [57]

KineAssist, a microprocessor controlled device is designed with small footprint and programmable modes. Switching into these modes, an impaired patient with malfunctioning of basic mobility functional level can be trained with higher risks consideration and outpatients with a disability can be trained with considering risk of falling.

Mechanism of the device is designed with turning and forward motion so that a device can follow the motions of patient (walking and turning).

Construction is as shown in the figure 9.13. Parallel standard legs of the system can pass through the normal standard door and also angled in 30 degrees offering patient more space for side-stepping.

Passive sliders and force sensors attached to the patient support structure detect patient’s intention to move. Control system of the device responses to the motion intention and move the base correspondingly.

Harness design is very important task. Primary functions of the harness are to maintain interaction between machine and user providing him/ her comfort as well as prevention from falling. It also stop the training slowly, smoothly without causing any pain to a patient. It is possible to set up harness of KineAssist in five minutes where other devices take almost 20 minutes. This time really matters during the training session of one hour.

Physiotherapist can use posture control to maintain desired posture, and for this, he can set pelvis and trunk components independently.

9.3.1.2 Components of KineAssist

Main components of the KineAssist are Mobile base and smart brace.

Mobile Base: Mobile base is moving part of the device that has wheels to perform turning or forward motion. This is a motor actuated platform which follows the motion of the user. Advantageous features of mobile base are it provides forward-backward and lateral motions, and it is not programmed. It just follows the user’s motion.

Smart brace: Smart brace is the mechanism that actually supports the user’s pelvis and trunk. It permits the natural relative movement that occurs during rehabilitation training. Subcomponents of the smart brace are:

Harness: It is permanently bounded to the support structure. Other than securing the patient, its structural components also acts as an anchor points for buckles and straps. Harness is designed in two pieces, upper level and the lower level. Torso gets secured by upper level harness where lower level harness is responsible for securing pelvis of the user. This two part construction is better for management from the point of view of user’s security.

Trunk and Pelvis Mechanism: This mechanism allows user’s bending motions. User is allowed to perform movements such as forward/backwards, left/right, hip rotation about forward axis, rotation about a transverse axis. Mechanism that supports the body dynamics is consist of two subcomponents: Pelvis support on the bottom and trunk support at an upper part. Through harness, trunk support is to be tied on the chest level. It is used for postural alignment, trunk stabilization, trunk perturbations etc. It may also bear some body weight during support mode of rehabilitation training. The pelvis support is responsible for stabilization of body. It is used as a body weight support system and vertical fall prevention mechanism as well.

Support Arm: Support arm that is mounted on the mobile base provides support to the trunk and pelvis mechanism.

KineAssist can be operated with several operating mode such as walking mode, challenge mode, postural mode, body weight support, perturbation, stabilization and strength training [57].

9.3.2 Clinical Experiments

Study compared differences between not only the sacral motion and EMG muscle activity but also individuals with post-stroke hemiplegia and individuals without any neurological impairment.

Aim of the first experiment was to test how the assistance of KineAssist can affect or alter the motion of healthy subject [58]. Experiment involved five healthy subjects and four functional tasks were assigned to them. Sit to stand, stand to sit, forward reach and walking forward [58]. Subjects were allowed to practice of each task with the device to ensure safety and comfort. Each task was completed with three different speeds categorised as slow, comfortable and fast [58]. This approach ensured reliability of the experiment.

Six EMG signals were collected, rectified, and summed for each muscle. Analysis of EMG signals allowed a percentage change calculation in performance with and without KineAssist [58].

In second experiment, ten subjects (more than six months post-stroke) were tested. Unlike the first experiment, in this experiment stroke patients were characterised according to their functional limitations using four clinical measures and patients were asked to perform three trials of each task at a self-selected speed (comfortable speed) avoiding speed variations [58].

Results of the experiment showed no alteration in kinematics of functional activities [58]. Results for a range of motion demonstrated very little differences in the overall kinematics ranges of motion. Only significant difference was noted at high speed of tasks and the vertical range of motion of healthy subjects [58]. In case of the stroke patient reduction was observed in vertical range of motion. EMG data proved an increase in muscle activity for both, healthy and stroke patient groups, more neural drive and efforts from subjects are required though [58].

Analysis of this experiment results also marked some limitations. First was programmed slower response time in the functional mobility activities that allowed subjects with weak motor control not to lose control of the device [58]. Second limitation was the necessity to compensate cantilever effect. Large load was required in the back of the device to maintain stability of the device when patient put larger weight on pelvic harness [58]. Upcoming version ‘alpha-two’ will be addressing these limitations [59].

As an overall result KineAssist have addressed several significant challenges in the field of rehabilitation robotics and those are:

- Pelvis interface that allows necessary control from the robot and degrees of freedom while supporting different body shapes.
- Movement of heavy robotic mechanism. It is a critical issue as it is designed with priorities with safety, sensation of very small motion and force exertion by the patient. Movement of mechanism should not disturb these functions.
- Transparency aspect (to provide assistance) was enhanced by the adaptive haptic algorithms.

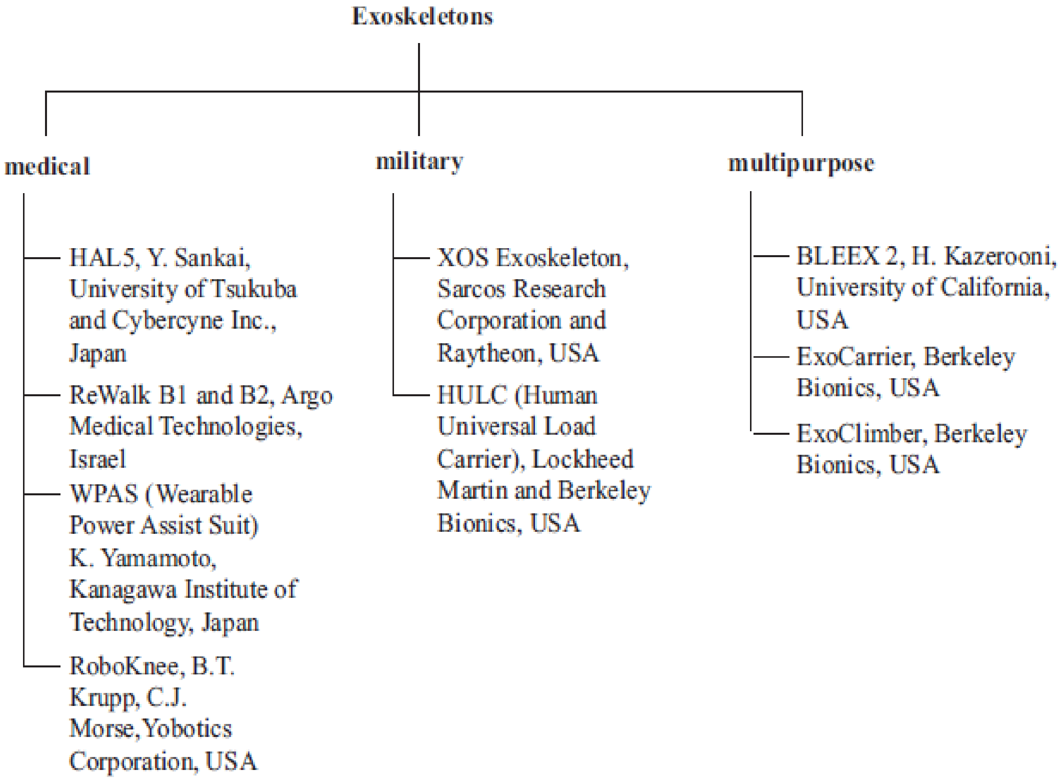
Recent clinical trials have been performed in Alexian Rehabilitation Hospital (data is not available) [60], and some experiments are going on at Rehabilitation Institute of Chicago (RIC) with new modified version of KineAssist [61].

CHAPTER 10: CURRENT EXOSKELETONS

By a definition, “exoskeleton is a distinctive kind of robot to be worn as an overall or frame, effectively supporting, or in some cases substituting for, the user’s own movements”.

Exoskeleton can be a full body exoskeleton (four limbs) or lower extremity (lower limbs only). Further exoskeletons can be classified according to their applications too [62]. Some of them are mentioned below in table 2.

TABLE 2: CLASSIFICATION OF STATE OF ART EXOSKELETONS BASED ON APPLICATIONS [62]



Actions of exoskeleton joints are controlled by user’s movements through human-robot interaction. Primary components of exoskeleton are: the main frame, the power supply, engines, the control system with sensors and actuators and batteries.

Feasibility, utility and effectiveness of exoskeleton can be defined by some features such as:

- The way and level of support to the user
- Human-robot interaction: EEG, EMG, pressure sensors, position sensors etc.
- The weight of the system
- Time required for the attachment and adjustment of exoskeleton braces. As an individual user's height and length of limb cannot be same, fitting and pre-setting of exoskeleton consumes time and efforts.
- Power supply. Long-lasting, rechargeable, portable, easy to transport and ready to use power supply/ batteries are needed for exoskeleton design.

Working principle of the exoskeleton is similar to any other autonomous system. Biosensors such as EMG sensors, pressure sensors, position sensors, angle sensors, gyroscope, encoders or accelerometer etc. collects sensory data from the human limb, following an intention of the user to move. Control system processes that data predicts intended move using pre-programmed movement pattern and sends a signal to the actuators. Actuators generate movements of exoskeleton joints.

History of exoskeleton can be traced back to 1860s. Current exoskeletons are not overnight inventions; huge research has been done in 19th century to reach at this stage of robotics. We are still in early stages of development of robotics. Continuous research is required for the advancement of robotics. Few state-of-art exoskeletons have been reviewed in this chapter.

10.1 HAL

Hybrid Assistive Limb (HAL) developed by Cyberdyne won an award for 'Invention and Entrepreneurship in Robotics and Automation (IERA) 2009' for developing the concept that can be applied to robotics for various fields such as physical training support, rehabilitation support, heavy labour support and entertainment industry as well [63] [64].

HAL possesses capability of expansion, improvement, enhancement and to support the physical capabilities of the user [64].

10.1.1 Technical evaluation

10.1.1.1 Construction and Mechanism

Leg structure of full-body HAL-5 has three DOF. Two actuated DOF at the hip and knee joints for flexion/ extension [5]. These DOFs are actuated by DC motors with harmonic drive placed directly on the joints [5] [65]. It has one passive DOF at the ankle joint in the sagittal plane for flexion/ extension [65]. Number of connection has been used to interface device with the user. These interfacing components include special shoe integrated with harnesses for calf and thigh equipped with ground reaction force sensors and a large belt for waist [5].

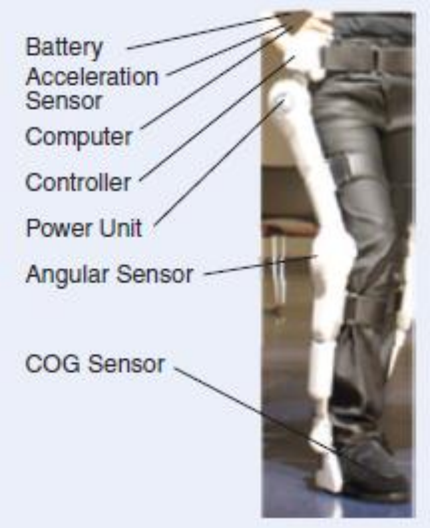


FIGURE 10.1: COMPONENETS OF HAL-5[65]

HAL-5 is designed with several sensing modalities for control. User carries potentiometers for joint angle measurement; skin-surface EMG electrodes attached below the hip and above the knee on the both sides on the user’s body, back side and front side. Accelerometer and gyroscope are placed in the backpack for the posture estimation.

HAL design includes lighter and compact power units, upper limb life, a more cosmic shell and longer battery life in comparison with its previous versions. As per the available latest specifications from Cyberdyne, manufacturer of the HAL; size of the robot is 1600mm and weight of full body robot is around 23 kg. Lower body robot weighs around 15kg. Its battery last around 2 hours 40 minutes in continuous operating time.

10.1.1.2 Control System

HAL-5 control is based on two control strategies, Cybernic Voluntary Control (Bio-Cybernic Control System) and Robotic Autonomous Control System. Combination of these control strategies has made one control system for HAL; Hybrid control system.

Cybernic Voluntary Control:

This control system is based on a bio-electric signal response from the user's body. When user attempts to move, brain creates electrical impulses and sends to the particular muscles (figure 10.2A). These faint electrical signals appeared on the skin surface, are sensed by electromyography electrodes (figure 10.2B). Observation of a bio-electrical signal pushes power unit to generate torque [66]. Torque drives lower limb components putting them into an action (figure 10.2C). This cycle generates intended movements for HAL-5 and thus moves the user (Figure 10.2D).

Robotic Autonomous Control System:

Every human movement is composed of several other elemental movements [66]. It is just like a software program. Program has to be developed using several other commands/ instruction. Final execution of the program takes place when all instructions are executed. In case of human motion, such as standing up from the chair; any movement can be considered as an aggregation of several other elemental movements.

HAL-5 control system uses a database that contains all information about the human body movements. Control signals form the database also gets amplified by the information collected through sensors attached to the body [66]. Using the database, HAL autonomously coordinates each motion so that power unit can assist it smoothly[66].

FIGURE 10.2: CONTROL SCHEME

In case of troublesome situation such as a collection of bio-electrical data is difficult or impossible due to some occurred in the central nervous system or in the muscle; HAL can be operated through Robotics Autonomous Control [66].

10.1.2 Clinical studies

HAL is mainly designed as an assistive device but it can be used for rehabilitation purpose too. Several studies have been conducted to test utility of HAL as a rehabilitation robot.

16 post-stroke hemiplegic patients, aged between 53-78 years were considered for the experiment. All patients were suffering from severe hemiplegia; four of them

were in need of assistance and remaining required supervision during walking [67]. All settings and assistance provided by physiotherapist were determined by the severity of muscle contraction for an individual patient and ability of ambulation [67].

Results of this experiment were not really positive. Walking velocity of 4 patients was significantly decreased due to muscle weakness of the trunk and extremity. However, three patients required supervision only grasped an efficient gait pattern while walking in HAL suit. Increase in stride length and walking velocity was recorded. Decrease in PCI values was also observed.

As a conclusion and explanation behind the obtained result, author has stated that HAL suit is not suitable for severe hemiplegic individuals. HAL uses bioelectric signals to generate power assistance; it becomes difficult to detect bioelectric signals from the muscles of patients suffering from severe hemiplegia. Improper measurement of bioelectric signals could lead to instability that may result into a decrease in stride length and walking velocity. Adaption of new gait patterns and coordination of movements are the necessities while the user is walking with HAL suit. This is not difficult for a healthy person but patient suffering from severe hemiplegia might fail in adaption and coordination [68] [67]. This condition might affect in a decrease of walking velocity of patient suffering severe hemiplegia [67] [68].

Results of patients with severe hemiplegia and needed supervision but have received gait training before were negative too. Patient who already have developed gait pattern could not cope up with new gait pattern generated by HAL suit; walking resulted in significantly disturbed gait pattern which may lead to instability and safety concerns.

Y. Sankai and team proposed an algorithm that can estimate the patient’s intention for the movements and accordingly control power generation [69]. This algorithm is based on the floor reaction force that was investigated through the walking support experiments for a patient with a sensory paralysis on both legs. Few initial testing confirmed that the algorithm could successfully estimate the patient’s intention for the movements. However, instability of body posture and difficulty in maintaining balance using walking frame with his hands were the drawbacks. Future work will be based on the development of the algorithm for the stabilisation.

Severely paralysed patients who has too weak muscle contraction and bioelectric signals cannot be sensed, should not use HAL suit. For the hemiplegic patients who needs supervision only but have developed gait pattern, HAL suit is not suitable. Less severe hemiplegic patients, healthy patients can use HAL to increase walking speed, stride length and may be to develop the gait pattern.

All these results have concluded the use of HAL-5 for hemiplegic patients. Further investigation is needed to know exact criteria and characteristics of patients who may gain more benefits from the use of HAL.

10.2 BERKELEY EXOSKELETON

Berkeley Lower Extremity Exoskeleton (BLEEX) has been known as an ambitious goal of DAPRA program. Its developers have claimed that BLEEX is first ‘Load bearing, field operational and energetically autonomous’ exoskeleton [5] [70]. Mechanism of BLEEX s most complicated compare to present state of the art robotic technologies [65].

BLEEX was designed with a 7DOF; 3 DOF at hip, 1 at the knee and 3 at ankle. Among 7 DOF, 4 DOF are actuated; 2 DOF at hip (hip flexion/ extension, abduction/adduction), 1 DOF at knee (knee flexion/ extension) and 1 at ankle (ankle flexion/ extension) [5] [71]. The ankle inversion/ eversion and hip rotation joints are unactuated and spring loaded whereas free-spinning ankle rotation joint is also unactuated. The kinematics and actuation requirements for designing and development of the exoskeleton is done by considering 75 kg human walking and using corresponding gait data for walking [5].

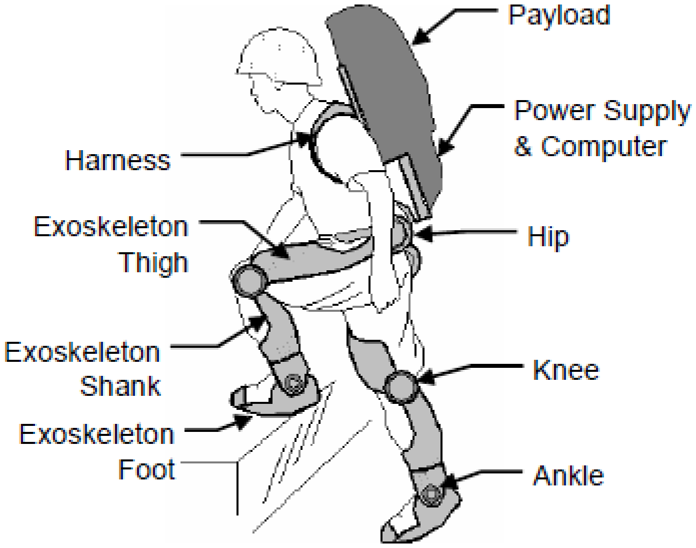


FIGURE 10.3: COMPONENETS OF BLEEX [70]

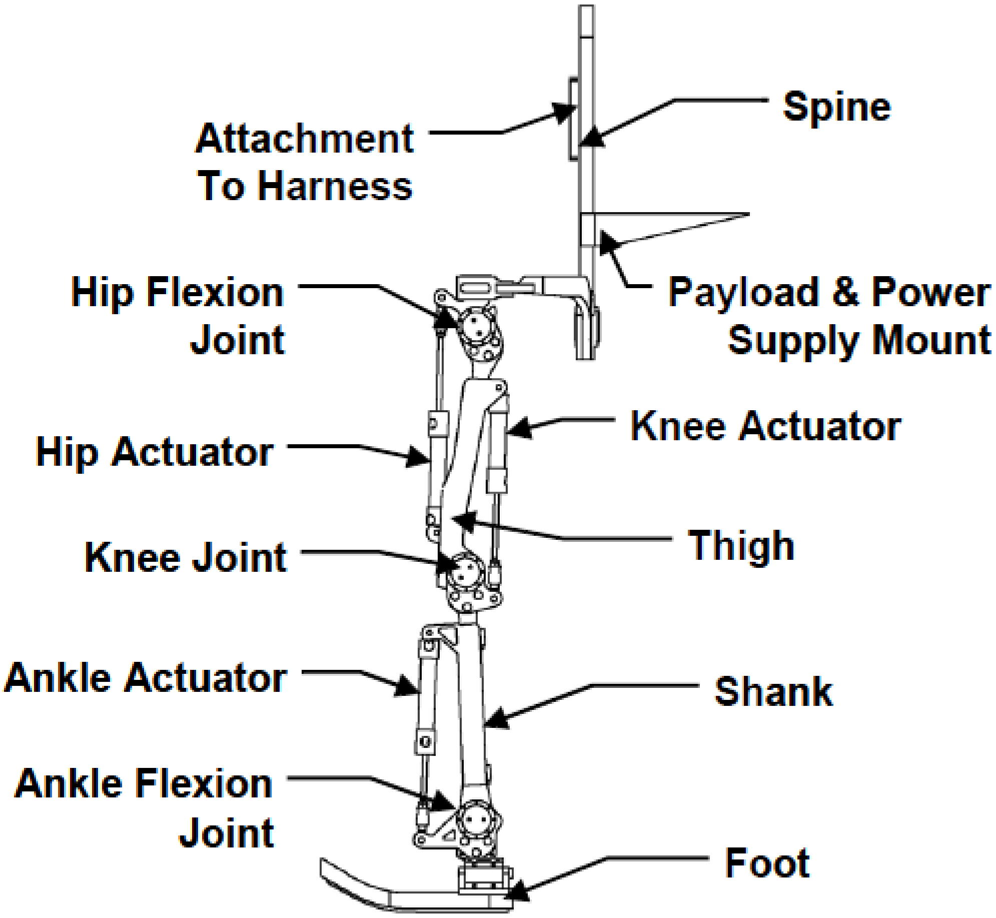


FIGURE 10.4: SIMPLIFIED BLEEX MODEL REPRESENTING MAJOR COMPONENTS [70]

Important feature of BLEEX includes:

- It is energetically autonomous i.e. it can carry its power supply
- A hip rotation joint configured between legs of exoskeleton so that it does not intersect with the user's hip joint.
- An ankle joint for inversion/ eversion is set at the lateral side of the foot in order to achieve simplicity.

For level-ground walking BLEEX requires an average of 1143 W of hydraulic power and 200 W of electrical power to drive electronics and control components [5].

Bidirectional linear hydraulic cylinder actuates BLEEX exoskeleton as they were "smallest actuation option available" based on their "high specific power". Later studies described that use of electrical motor actuation is more efficient for the power consumption than hydraulic actuation [72]. Weight of electrical motors was almost twice of hydraulic actuators though [72].

Control scheme of BLEEX prefers sensory information form the exoskeleton rather than sensory information from human-machine interaction [5] [72]. Measurements based on exoskeleton only makes user feel very little forces [72]. Exoskeleton can balance on its own but for walking user must provide forward force to the exoskeleton. 8 encoders and 16 accelerometers provide sensory information to the control system such as angle, angular velocity, and angular acceleration of all actuated joints, load distribution sensor and foot switches. This control scheme is complicated but effective to generate locomotion especially when contact location of human-machine interface in unpredictable and unknown [72].

BLEEX exoskeleton has demonstrated walking speed up to 0.9 m/s with load of up to 75lb and 1.3 m/s without the load.

New device that is currently under testing; has been designed with electrical actuation in combination with hydraulic actuation that has reduced its weight by almost half (~14kg).

Hydraulic- Electrics Power Unit (HEPU) was specially designed for BLEEX [72] [5]. HEPU provides hydraulic power for locomotion and for computations of components and sensors it provides electrical power [72] [65]. HEPU is capable of fuelling and combines the high specific energy of hydrocarbon fuels with the high specific power of hydraulic actuator system [72].

BLEEX is a robotic multipurpose exoskeleton. It can be useful for medical applications as well as military applications. BLEEX and other similar technologies can be used to mobilise wheelchair users. Wheelchair users can possibly walk for hours depending on their medical complexities. It can also avoid secondary medical conditions such as risk for diabetes, obesity and cardiovascular conditions that come after spending long span (probably few years) on a wheelchair or in immobilised condition [73]. Use of such robotic mobilising techniques can also avoid the pain that arises due to overuse of upper body muscles [73].

10.3 REWALK

ReWalk is an exoskeleton developed by Argo Medical Technology to provide a solution for mobility to wheelchair users, spinal cord injury survivors or other neurological impairments. ReWalk can enable user to stand, walk, and climb stairs up or down or other similar activities that are important in daily lives [74]. ReWalk is a promising technology that may enhance ADL by reducing the need of rehabilitation and re-hospitalisation as well as improving physical health by carrying out routine ambulatory functions [74].

ReWalk exoskeleton offers user-initiated mobility. It includes support suit made up of a light wearable braces that integrates an array of motion sensors, actuation motors at the joint, and a computer system that provides sophisticated control and safety algorithms and rechargeable batteries [74].

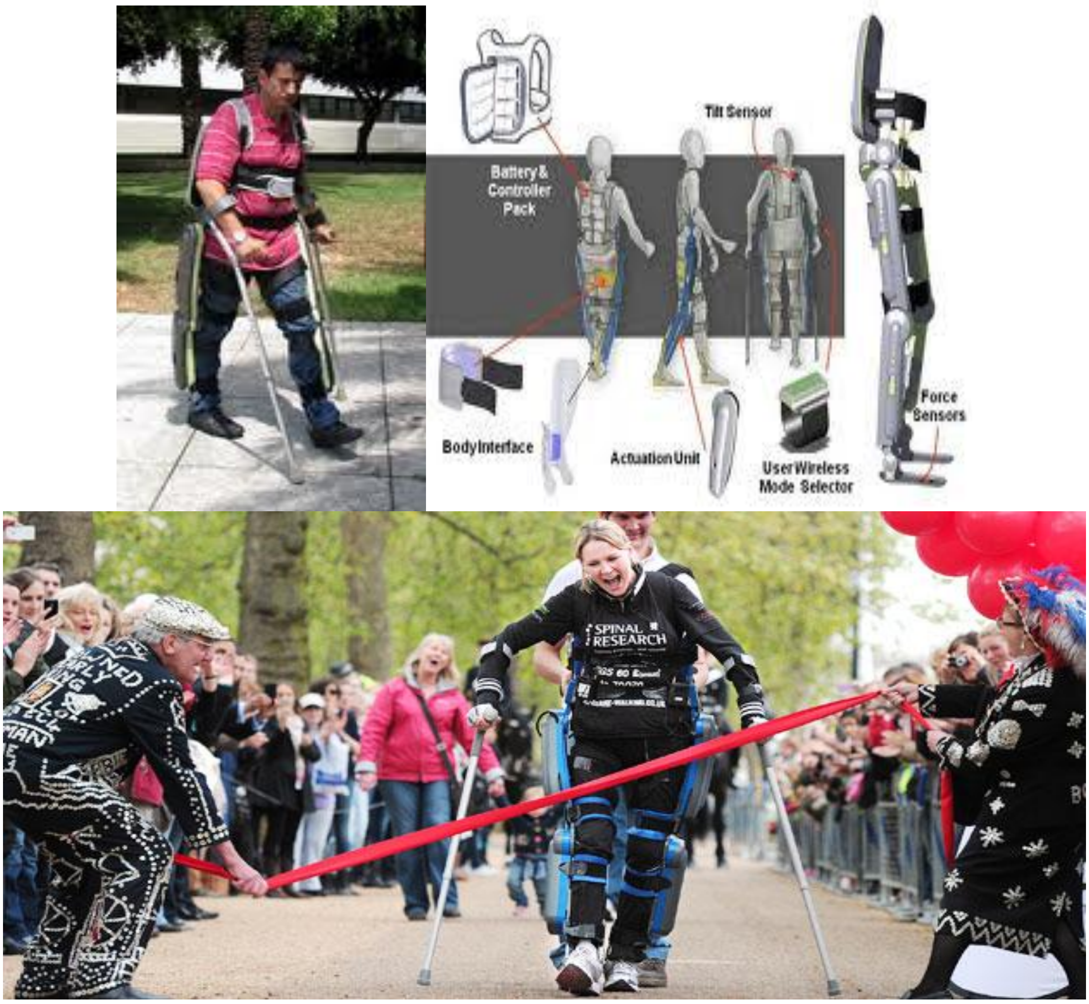


Figure 10.5: Left from top: User walking with ReWalk, Right from top: Constructional view of ReWalk, Bottom: SCI survived patient, Claire Lomas who completed London Marathon 2012 in 16 days wearing ReWalk [70].

Actuated DOF of ReWalk at hip and knee are actuated by DC motors [75]. The ankle joint is unactuated [75]. Its control system is dependent on human-machine interface where user is actively involved in controlling the suit. Control processor controls movements by considering changes in control of gravity (COG). Crutches are provided to ensure safety and stability.

Prerequisites for ReWalk uses are the capability to use upper limb so that control on crutches will be possible while walking and healthy cardiovascular system as well as bone density[74]

ReWalk exoskeleton has been manufactured in two categories: ReWalk-I and ReWalk-P.

- ReWalk-I is developed for institutional use. This device is multi-user rehabilitation training device that can provide a therapeutic and physical training for intensive locomotion therapy replacing or supplementing large, expensive gait trainers with complicated mechanism [74]. Use of ReWalk at rehabilitation centres may reduce the cost spent on therapeutic activities. Two sizes are available for ReWalk-I to accommodate user’s height. Rehabilitation centres in Europe and USA are using this device.

- ReWalk-P is being developed for personal use and it is still under development. This device will be targeting individuals who have gone through a medical examination and have successfully completed the rehabilitation training program [74]. This device will be useful for daily indoor and outdoor activities. ReWalk-P is due to enter in the market in second half of 2012 [74].

10.4 MINDWALKER

MindWalker is a 3 years funded project by EC FP7 [76]. EC FP7 is a ‘Framework Program for Research and Technology’ sponsored by European Commission which will last for seven years, 2007 to 2013 [77]. MindWalker lower limb exoskeleton is, as its name indicates, based on mind control concept. Unlike other available current robotic technologies, MindWalker uses Brain Computer Interface (BCI) to control the system.

Primary aim of the project is to provide mobility to severe SCI patients or severely impaired patients who are not able to produce enough EMG signals to receive rehabilitation training from available robotic devices [76].

10.4.1 Technical Evaluation

MindWalker project involves [76]:

- Non-invasive BCI technology (avoiding implantation of micro-array electrode chip into the brain that eliminates the risk of infection)

- Exoskeleton mechatronics and control technology

- Virtual Reality (VR) simulation for training purpose

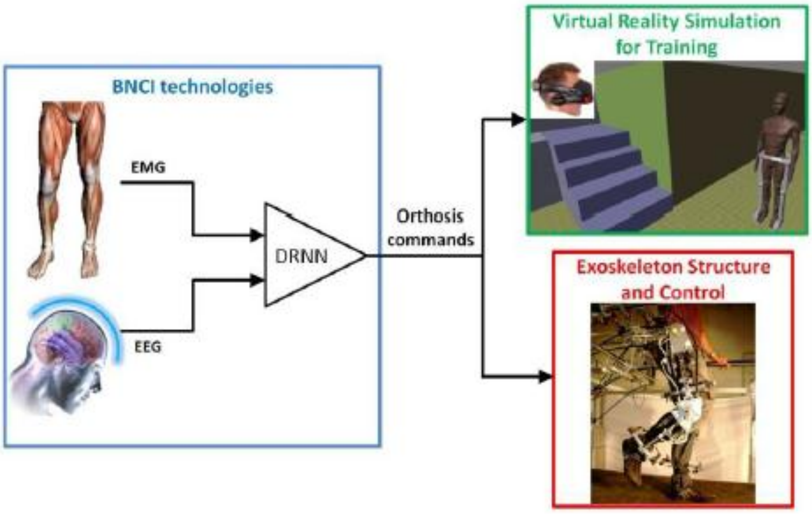


FIGURE 10.6: OBJECTIVES OF MINDWALKER [75]

MindWalker is based on four key systems: Dry Electroencephalography (EEG) Cap for brain signal measurement, BCI processing chain to provide efficient interfacing between brain signals and control system of machine, exoskeleton mechanism and Virtual Reality Training Environment (VRTE).

EEG Cap: To acquire brain signals special lightweight and dry electrodes cap is being developed [76]. Fast and convenient signal acquisition for daily activities of user is expected. Brain signals, indicating intended movement are further processed in BCL processing section.

BCI: Brain Computer Interfacing is one of the most challenging areas in rehabilitation robotics. It translates EEG signals into actuation control signals. Pre-processed spatial and temporal signals are given to the Dynamic Recurrent Neural Network (DRNN) [76]. DRNN is already trained with different database of walking patterns. So after receiving intentional brain signals, DRNN provides corresponding kinematic angles [76].

Exoskeleton Mechanism: Exoskeleton is being designed in a way to provide weight support and stability to the user. A low level model controller ensures the balance of user and system during walking [76]. A high level controller obtains 3D model of the frontward environment using exteroceptive sensors, securing the system even in risky situations such as obstacles, uneven ground level [76].

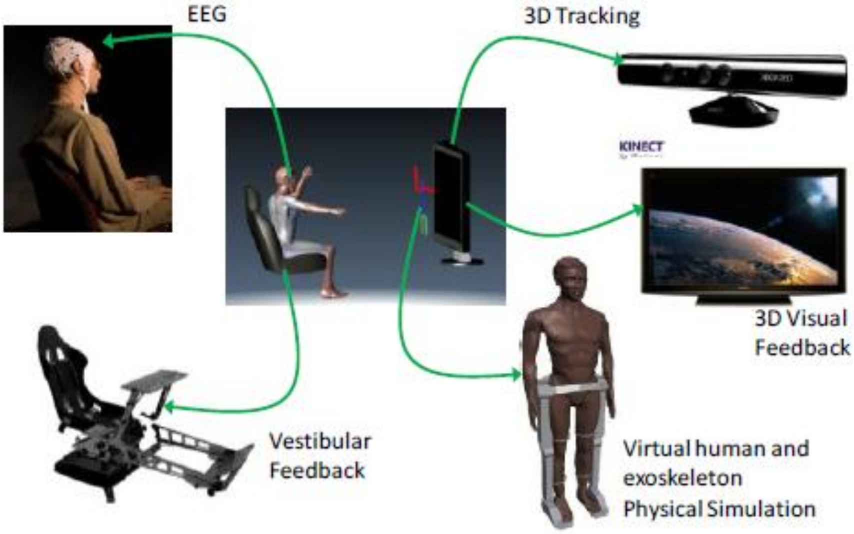


FIGURE 10.7: VRTE SET-UP [75]

Virtual Reality Training Environment (VRTE): Before using MindWalker system, familiarisation and training with the system is necessary. VR set-up is under development. It will provide the environment to the user to feel sensation of controlling an exoskeleton through BCI interface [76]. Set-up will be providing a 3D visual feedback and actuated seat to provide vestibular feedback [76]. Biological parameters can be monitored during training session [76].

MindWalker is under construction. It’s an emerging hope for severely impaired patients to improve their DAL as well as to avoid secondary complication. Other application of the MindWalker includes use as a space robot.

10.5 REX BIONICS

Rex stands for **R**obotic **Ex**oskeleton which is an exactly vertical wheelchair. Basic aim behind its development was to mobilise impaired patients using their own limb.

Unlike other current exoskeletons, Rex doesn’t need any interfacing with muscles of nerves as it is controlled by joystick, not sensory information [78].

FIGURE 10.8: EXOSKELETONS DEVELOPED BY REX BIONICS [77]

Its weight is near about 85 pounds (39kg). Maximum speed Rex can reach if 11 ft/min (3 m/min). Battery life can last for two hours. Rex can support various movements such as standing, walking, climbing up and down stairs, ramps or slopes. Rex System doesn’t need crutches [78].

A prerequisite criterion is not critical for Rex as there is no need of human-machine interfacing (EMG signals). Anyone who can operate joystick, with height between 1.46m and 1.95m, with weight less that 100kg and hip width of 380 or less can use Rex.

10.6 eLEGS

FIGURE 10.9: ELEGS [78]

Exoskeleton Lower Extremity Gait System (eLEGS) is another ambitious project of Berkeley Bionics, California, USA. eLEGS has been mentioned as “Wearable, artificially intelligent, bionic device” that has offered a feasible option for wheelchair to make paraplegic patient’s life better [79] [80]. In first stage of evaluation, device has been going through a medical supervision at rehabilitation centres [79].

eLEGS uses force and motion sensors to predict intention of movement. Control system actuates corresponding joints and angles. Important feature of the device is it can provide “unprecedented knee flexion” [79]. Allowed motions are walking, standing for an extended period, stand form sitting position and vice versa [81] [80].

Weight of Exoskeleton is around 45 pounds (20kg), maximum speed goes up to 2 m/s and battery life can last for 6 hours [81]. For support and stability, eLEGS requires crutches [81].

Any individual who can transfer himself/ herself from the chair and height is between 5’2” to 6’4” with weight 220 pounds or less can use eLEGS [81].

10.7 MIT EXOSKELETON

Professor Hugh Herr and his team at the Massachusetts Institute of Technology has been developed a quasi-passive exoskeleton, MIT exoskeleton. Purpose of this innovation was to create a heavy load carrier to off the burden from soldier’s back or to provide assistance in walking to the paraplegic individuals.

10.7.1 Technical Evaluation

The concept of MIT exoskeleton is based on the utilisation of passive dynamics of human walking to develop lightweight, effective and more efficient robotic device [82]. Use of passive dynamics to create wearable robot for lower limb suggest that mechanical structure utilises exchange of elastic, kinematic and gravitational energy [82]. This structure makes exoskeleton more energy efficient than conventional walking machines those are controlled through zero moment point (ZMP) technique [82]. As MIT exoskeleton is based on passive dynamics, it doesn’t require actuators to drive the joints. Whole design is dependent on controlled release of energy stored in passive components such as springs, dampers during walking. Selection of passive components of exoskeleton is based upon analysis of kinetics and kinematics of human gait patterns [82].

Hip portion is designed with a 3 DOF, flexion/extension, abduction adduction, and rotation; these all hip movements are spring loaded. In this design hip and ankle rotation movements are allowed in non-sagittal plane. A cam mechanism is also included in the design to provide compensation for the gap between the thigh of the exoskeleton and the user because of the joint offset during abduction/ adduction [82].

FIGURE 10.10: MIT EXOSKELETON[81]

The knee joint of the exoskeleton has been designed with magneto-rheological variable damper that dissipates energy in controlled fashion during gait cycle [82]. For the ankle joint, separate spring is attached for dorsiflexion/ plantar flexion, carbon fibre plate is attached to the boot and carbon fibre spring under the heel in order to provide aid for lifting [82].

An artificial elastic spine is mounted on the backpack that makes coronal and sagittal plane movements possible for the user [82].

Control of all passive components is based on the sensory information acquired from a set of full-bridge strain-gauges as well as a potentiometer placed on the knee joint [82].

Weight of the exoskeleton is 11.7kg without any payload. During loaded walking, it requires only 2W electrical energy. Electrical power is needed to control the damper at knee joint.

10.7.2 Clinical Evaluation

In the experimental evaluation device successfully supported a 36 kg load while walking at the speed of 1 m/s. This experiment also demonstrated that 80% load of the 36 kg was transferred to the ground during the single-support phase [82].

10 % increase in walking metabolic cost of transportation of the user loaded with 36 kg was shown into metabolic studies [82]. 10% more oxygen consumption by the user was not an encouraging result. This was the first experimental study, performed to test metabolic cost associated with passive exoskeleton. However, none of the study has succeeded to develop passive exoskeleton that will reduce metabolic cost than standard backpack load carriage exoskeletons [82].

Further investigation of MIT exoskeleton reported significant reduction in metabolic cost when exoskeleton was compared against same exoskeleton without springs attached at the hip and the ankle and the damper at the knee joint emphasising the importance of passive components [82].

Though MIT exoskeleton seems promising technology as it is lightweight, low energy consumption, almost 80% of load carriage, major drawbacks are increase in metabolic cost and impact on natural walking gat pattern. These obstacles are needed to be cleared with further research so that MIT exoskeleton can be used as an effective assistive technology for lower limb.

CHAPTER 11: DISCUSSION AND CONCLUSION

11.1 Discussion

Patients surviving neurological disorders including spinal cord injury, Parkinson’s disease etc. or lost limbs following to amputees or accidental injuries suffer in meeting the challenges of their daily life. According to severity of disability; patients cannot balance themselves, cannot stand, and may have weakness in their limbs that affect walking pattern and capacity. For a long time physiotherapy interventions have been the only practical intervention to assist in promoting the partial of the motor function. In most cases this therapy relies on repetition of the same movement or physical exercise with the support of therapist. But this requires one-to-one intensive therapy which is often difficult to arrange and difficult to sustain over the time necessary for benefits to occur. Accordingly, physiotherapy has some limitations. One of which is that it is labour intensive. In some case up to three therapists can be required to support patient’s body weight, one therapist to maintain posture and two additional therapists to move the legs in the desired trajectory. In such cases the cost of therapy is high and the number of patients that can be treated is low. These physical effort by the therapist is also a high demand and fatigue and tiredness can limit therapy effectiveness.

To overcome over-come the aforementioned hurdles ‘autonomous systems’ were considered as an option and robotics were introduced in the rehabilitation field. In this report, we reviewed some state of art robotic devices. Some results of clinical studies are showing encouraging progress. However, despite huge research in this field, we are not able to over-come all obstacles yet. In this study; advantages as well as limitations of use of robotics for rehabilitation were discussed.

Treadmill gait trainers are the most studied devices. Devices such Lokomat, LOPES, ALEX are well established commercial systems. Undoubtedly, robotic body weight support system in combination with treadmill gait trainer is viewed by the clinics using them as effective aids to patient rehabilitation. Clinical trials have revealed that they are feasibility, safe and effective when compared with conventional therapy. But these devices have some limitations. Access to the physiotherapists to the patient during session is limited. Therapist cannot easily correct misaligned posture during the session without stopping and repositioning the patient in the device which is time consuming process and frustrating to the patient and therapist. Devices are heavy and bulky. Patients, who performed well on treadmill, often fail to maintain performance when engaging in over ground walking. There therefore is still a need to have patients transfer to over ground walking training at some point in their rehabilitation.

Few BWS treadmill gait trainers such as ALEX uses templates recorded from healthy subjects as a reference trajectory. Dependency on a standard gait model for limb guidance is therefore also a limitation as limb trajectory cannot be the same for every individual. Improving the ability to fine tune trajectory would offer new advantages to the rehabilitation programmes.

Where robotic devices can prove to be effective is in the early rehabilitation of severely disabled patients who may have no initial scope for over ground training. For less severe patients standard physiotherapy is equally good.

To address the reference trajectory problem, active foot orthosis device, combination of PAM and POGO use mean trajectories recorded from the patient himself for training. But this is not possible with severely paralysed patients. But with this approach there is a need to introduce more advanced control algorithm to prevent de-synchronisation and allow the maintenance of fixed speed and walking patterns. The added complexity also comes into play through the need for better effective sensor technology and control over limb movements.

Footplate manipulators are nothing but modified BWS treadmill trainers. These devices have been designed to provide training of climbing stairs, ramps, walking at different speed etc. Training with footplate manipulators such as Haptic Walker has been provided more effective results than BWS treadmill training. However, these devices are heavy and bulky and may be unsafe in certain circumstances Patient in early stages of injury are not recommended to use these devices for rehabilitation training. Recently developed devices such as LLRR have attempted to address these concerns. Effective sensor system and control system have succeeded to prevent hazardous situations such muscle injury resulting from spasms but further development are necessary before wide spread usage will be possible.

In comparison with footplate manipulators and BWS treadmill trainers, no significant differences are recorded in healthy or sub-acute patients. Result of case studies performed with severe stoke patients concluded that footplate manipulators are more effective devices than treadmill gait trainers (REFS). But it should be noted that the numbers of patients tested is small and key factors that give improved performance were not provided by the researchers.

Cable driven robot is also promising technology in terms of safety and feasibility for rehabilitation. There is no extensive literature available about this type of devices. STRING-MAN is cable driven robot and its experimental results are encouraging. It motivated users for self-training for walking. Unlike footplate manipulators, these devices can be used to provide training to bedridden or non-ambulatory patients too. Major concern is complexity of kinematics and dynamic models.

Stationary gait trainers are useful to provide rehabilitation in early stages, at the bedside of the patient. These are portable small devices that are easy to transport and are effective in early stages; but as patients progress they should move to receive proper rehabilitation training at rehabilitation centres.

Exoskeletons are the most promising devices for the rehabilitation in this era. Exoskeletons are highly dependent on selection of sensors, actuators, power supply unit and feasibility of the frame. Current challenges are effective sensor technology and control system that can effectively work in real-time and offer safe overground walking control.

Besides the vast research in wearable robotics field, some recent and most advanced exoskeletons such as BLEEX and ReWalk have not been disclosed in due to commercial or military interests. In the available literature researchers have presented their views about biomechanical aspects, sensor technology, actuators, control system, safety management etc.

To address shortfalls of rehabilitation and assistive technologies, several solutions with prototype devices have been proposed. Suggest technologies often propose contrasting solutions. Assisted joints, the number of DOFs and degree of kinematic complexity are all under investigation. Researches have provided some justification supporting their choice of designing aspects and strategy. But often no quantitative data has been provided or released into the public domain. So, it is difficult to make any statement about how effective these exoskeletons are; which aspects make them effective [77]. Moreover, no pre-requisite criteria for selection of designing have been mentioned.

Currently available information and experimental studies can recommend further modifications but due to lack of quantitative evaluation, it is hard to conclude how effective these recommendations will be [77]

All this work is in experimental stage. Due to lack of knowledge of human body and how it reacts to the externally attached joints; definite recommendations cannot be proposed to design an ideal exoskeleton.

As an end note, the view reached is that further research is needed. Exoskeletons such as HAL-5, ReWalk are performing well but these devices are dependent on EMG signal detection that demands very efficient sensors and intelligent control system. Quality of EMG detection is very poor while interacting with highly disabled patients and this will be a limiting issue. Experimental studies have also demonstrated that exoskeletons with full guidance control are not suitable for subacute stroke patients or subjects who still have some control on their motor functions. These patients gain no rehabilitation benefit from the device and often fight against its motion. Accordingly, these are truly assistive technologies best suited to the patient with total paralysis of the legs. So if we wish to provide rehabilitation effective interaction between machine and robot is needed that promotes adaptation and relearning of motor function. If EMG cannot be detected, BCI (brain-computer interface) can be the alternative solution.

Proposed MindWalker design is based on the BCI technology where EEG is measured instead of EMG. This technology is really promising in order to assist lost limb functions.

11.2 Conclusion

Though robotic system has been proven more effective than conventional therapy, robotic system is not a replacement for physiotherapist. Robotic rehabilitation works better in combination with conventional exercises. In present situation, robotic system cannot take effective decisions regarding method and progress of rehabilitation training for the user as an experience physiotherapist.

In this technical review several clinical experiments, evaluation experiments were studied. Conclusions of most of studies were not confirmed due to limitations of selection and small group size of subjects. Disregarding their sex, age, and severities were studied in the same experiments that might affect results. Results may differ with large number of subject with same medical background would be studied.

Advancement in robotic devices has reached at the satisfactory stage. Robotic devices have been proved effective for rehabilitation and assistance purpose. Recently developed synchronisation algorithms, safety management have ensured safe and reliable tools for rehabilitation. At the present time the suitability of the existing devices for individual types of patient is not established fully nor is the dose or intensity of training well defined.

Current state-of -art exoskeletons are emerging as a safe and comfortable devise. There is increasing demand and need for exoskeletons but its suitability as deployable rehabilitation devices is still doubtful. More research and systematic analysis is needed. Research on more effective sensing technology, intelligent control system, portability and long lasting power supply unit is needed further in order to provide efficacious means of rehabilitation and assistive technology.

Despite current challenges and limitations, robotics has emerged as a positive hope in rehabilitation field. Further research is needed to address current challenges.

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