# 1

# Rehabilitation Technologies: Biomechatronics Point of View

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## 1. Introduction

Rehabilitation aims to bring back the patient's physical, sensory, and mental capabilities that were lost due to injury, illness, and disease, and to support the patient to compensate for deficits that cannot be treated medically (http://www.ehendrick.org/healthy, June 2010). After the Spinal Cord Injury (SCI), stroke, muscle disorder, and surgical operation such as knee artroplasticy, patients need rehabilitation to recover their movement capability (mobilization) (Bradly et al., 2000; Inal, 2000; Metrailler et al., 2007; Okada et al., 2000; Reinkensmeyer, 2003 and http://www.manchesterneurophysio.co.uk, November 2010). The number of those who need rehabilitation is steadily increasing everyday. Parallel to this, equipment and techniques used in the field of rehabilitation are becoming more advanced and sophisticated.

On the other hand, mechatronics, an interdisciplinary science, is a combination of machinery, electric-electronics and computer sciences plays an important role in rehabilitation technologies. In particular mechatronics systems provide important benefits for movements that are related to physical exercises in rehabilitation process.

**Biomechatronics** is a sub-discipline of mechatronics. It is related to develop mechatronics systems which assist or restore to human body. A biomechatronic system has four units: Biosensors, Mechanical Sensors, Controller, and Actuator. Biosensors detect intentions of human using biological reactions coming from nervous or muscle system. The controller acts as a translator between biological and electronic systems, and also monitors the movements of the biomechatronic device. Mechanical sensors measure information about the biomechatronic device and relay to the biosensor or controller. The actuator is an artificial muscle (robot mechanism) that produces force or movement to aid or replace native human body function (http://www.ece.ncsu.edu/research/bee/biomd, ND). Typical usage area of biomechatonics is orthotics, prosthesis, exoskeletal and rehabilitation robots, neuroprosthesis. In this chapter, rehabilitation robots will be discussed in terms of bio-mechatronics systems.

Especially in the last ten years, the number of studies about robots in the rehabilitation area has increased due to developments in actuator, sensors, computer and signal processing technologies. Some important reasons for the utilization of robots in rehabilitation can be listed as follows (Krebs, 2006):

- Robots easily fulfill the requirements of cyclic movements in rehabilitation;
- Robots have better control over introduced forces;
- They can accurately reproduce required forces in repetitive exercises;
- Robots can be more precise regarding required therapy conditions.

Rehabilitation robots can be classified into four groups:

- To assist disabled people in special need with their daily life activities,
- To support mobility,
- To assist social rehabilitation (Cognitive robotics)
- To assist therapists performing repetitive exercises with their patients (therapeutic exercise robot).

In this chapter, rehabilitation robots are introduced and explained in terms of functionality, control methods and equipment technology. The theory and terminology is given in Section II, first devices and tools are explained in Section III, rehabilitation robots are explained in terms of mechatronics in Section IV, types of rehabilitation robots are described in Section V.

## 2. Terminology of rehabilitation

### 2.1 The exercise movements in physical therapy and rehabilitation

There are five basic movements in Physical Therapy and Rehabilitation (Griffith, 2000). They are:

- *Extension*: The act of straightening or extending a limb.
- *Flexion*: The act of bending a joint or limb in the body by the action of flexors.
- *Abduction*: Abducting of a limb from middle line of body
- *Adduction*: Adducting of a limb to middle line of body
- *Rotating:* Rotating of a limb

### 2.2 Exercise types in physical therapy and rehabilitation: (Kayhan, 1995)

**Passive Exercise:** This exercise is performed for the patient by another person (nurse or therapist) or by an exercises device (robotic device or CPM). It is usually applied to patients who do not have muscle strength.

**Active Assistive Exercise:** As the patient develops the ability to produce some active movement, active exercise begins. Assistance can be provided manually by a therapist, by counterbalancing with weights or by gravity. This exercise is helpful in increasing the strength of the patient.

**Active Exercises:** These are the purposeful voluntary motions that are performed by the person himself, without resistance and with or without the aid of gravity. Active exercises can be resistive such as isotonic, isometric and isokinetic. They are called *resistive exercises*, as well. **Isometric** exercise involves the application of constant resistance to the patient on the range of motion (limb angle does not change). I**sotonic exercise** is applied to strengthen patients who suffer muscle contractions. Unlike isometric exercise, a constant resistance force is applied to the patient for the duration of the movement. **Isokinetic exercises** refer to resistance exercise performed at a constant preset speed. The speed is kept constant by resisting accommodating to muscle effort (torque). Isokinetic exercise should be applied by a machine. There some isokinetic machines such as BIODEX, CYBEX, Kin COM etc.

**Manual exercise:** These kinds of exercises are applied by physiotherapist. Physiotherapist decides that which type of exercise should be applied to patient. At this point, expertise of PT has a significant importance.

## 3. Conventional tools and devices in rehabilitation

In physical therapy and rehabilitation, some tools such as dumbbell, elastic band, rope and some mechanism in order to perform range of motion and strength exercise have been used for long time. At the end of 1970's, a significant development occurred. First electromechanical device in rehabilitation named as continuous passive motions (CPM) was developed and used (Fig 1). CPM gained a new momentum about usage of new technologies in rehabilitation. It was able to perform repetitive exercise motion on desired velocity and duration.

Fig. 1. Continuous Passive Motion Device (http://www.arthroscopy.com/sp06001.htm, October 2011)

The first clinical results about CPM's treatment effect were released by Salter and Simmonds in 1980. (Salter & Simmonds, 1980)

Then the computer controlled isokinetic machines which can also perform passive, isotonic and isometric exercises were developed. These machines were able to record exercise results. They are very important in order to follow rehabilitation period. The best known isokinetic machines are BIODEX (Fig.2), CYBEX and KinCOM. In this machine, a motor is used to generate resistance to movement. In previous models generated torque value was obtained via calculations. However modern isokinetic machines have load cell or force sensor to this regard. Today, they are being used in many medical centers.

At the middle of 1980's, some studies which were related to rehabilitation robotic were started to realize. For instance, Khalili & Zomlefer developed a robotic system for rehabilitation of joints and estimation of body segment parameters (Khalili & Zomlefer, 1988). Howell et al. used a robotic manipulator in order to rehabilitate the children (Howell et al., 1989). Kristy and et al. developed a smart exercise system which allows that the patient can perform some rehabilitative tasks with robot and computer. (Kristy et al., 1989)

Fig. 2. BIODEX Isokinetic Machine (http://www.biodex.com, October 2011)

They were the first research studies on rehabilitation robotic. Detailed information about them is given in following sections.

## 4. Rehabilitation robotics in terms of mechatronics

### 4.1 What is mechatronics?

The definition of mechatronics has evolved since the original definition by the Yaskawa Electric Company. In trademark application documents, Yaskawa defined mechatronics in this way (Kyura & Oho, 1996; Mori, 1969)

*"The word, mechatronics, is composed of "mecha" from mechanism and the "tronics" from electronics. In other words, technologies and developed products will be incorporating electronics more and more into mechanisms, intimately and organically, and making it impossible to tell where one ends and the other begins."*

At recent year another definition suggested by W. Bolton (Bolton, 1999);

*"A mechatronic system is not just a marriage of electrical and mechanical systems and is more than just a control system; it is a complete integration of all of them."*

The interaction of the other areas and place of the Mechatronics system design are shown below clearly. (Craig, 2010)

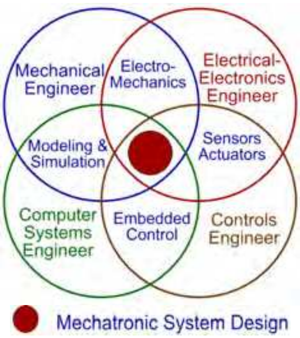



Fig. 3. Mechatronics System Design

As it is shown at the figure, Mechatronics is located at the middle of the clusters. Mechatronics system design involves Mechanical Eng., Electric-Electronic Eng., Control Eng. and Computer Eng. The study of Mechatronics systems can be classified as follows. (Bishop, 2002)

- Physical Systems Modeling
- Sensors and Actuators
- Signals and Systems
- Computers and Logic Systems
- Software and Data Acquisition

Robotics, motion control and conventional mechatronics, intelligent mechatronics, Human supported/based mechatronics, IT based mechatronics, micro and nano mechatronics and biomechatronics are application areas of mechatronics. (Akdoğan, 2004)

Biomechatronics and biomedical applications of mechatronics are emphasized in this chapter. Bio-industry requires mechatronics systems which have high quality and high precision. At Bio-Industry mechatronic systems are used for surgery, rehabilitation and prosthesis applications. Some biomechatronics systems are designed for these purposes are shown below.

a. Da Vinci Surgery Robot (http://www.roswellpark.org/robotics/about/da-vinci-surgical-system, December 2011)

b. Bionic Hand (http://www.BeBionic.com, December 2011)

**c.** Locomat ( Bernard et al., 2005)

Fig. 4. Biomechatronics Systems

Biomechatronics refers to a subset of mechatronics where aspects of the disciplines of biology, mechanics, electronics and computing are involved in the design and engineering of complex systems to mimic biological systems. Other definition of biomechatronics is suggested as follows:

*"Biomechatronics is an applied interdisciplinary science that aims to integrate mechanical elements, electronics and parts of biological organisms. Biomechatronics includes the aspects of biology, mechanics, and electronics. It also encompasses the fields of robotics and neuroscience.* (http:// www.wikipedia.com/biomechatronics, 2011)

Another definition of biomechatronics is suggested by H. Witte (Witte et al., 2005)

*"Biomechatronics is the development and optimization of mechatronic systems using biological and medical knowledge. This strategy may be exemplified by bionically inspired robotics: identification of biological principles and their transfer into technical solutions extends the engineer's toolbox.*

### 4.2 Actuators

In many mechatronics systems, movements or reactions to a situation are available. These movements and reactions are provided by system elements which produce force and torque. The displacement and acceleration are provided in the moving parts by these produced torque and force. Actuators are the elements in the systems that produce these torque and force. Electrical Motors, Hydraulic-Pneumatic actuators and their applications in rehabilitation robotics are mentioned in this chapter.

#### 4.2.1 Electrical motors

Electromechanical actuators convert electrical energy into mechanical energy. Electromechanical actuators are divided into varieties between their energy converter mechanism such as electromechanical, electromagnetic, electrostatic and piezoelectric. The differences in electric motors are mainly in the rotor design and the method of generating the magnetic field. Some common terminologies for electric motors are: (George & Chiu, 2002)

The components of electric motors;

- Stator: It generates the appropriate stator magnetic field. It can be made of permanent magnets or copper windings. Magnetic field is created with these magnets and copper windings in the motor. Stator can be found inside or outside of the motor.
- Rotor: is the rotating part of the motor. Depending on the construction, it can be a permanent magnet or a ferromagnetic core with coil windings (armature) to provide the appropriate armature field to interact with the stator field to create the torque.
- Armature: is the rotor winding that carries current and induces a rotor magnetic field.
- Air Gap: It is the small gap between the rotor and the stator, where the two magnetic fields interact and generate the output torque.
- Brush is the part of a DC motor through which the current is supplied to the armature (rotor). For synchronous AC motors, this is done by slip rings.
- Commutator is the part of the DC motor rotor that is in contact with the brushes and is used for controlling the armature current direction.

Electrical motors are classified two major types as DC Motors and AC Motors. Because of the industrial requirements, there are many types of motors outside of three two major types such as stepper motors, linear motors and servo motors. These five major electric motor types are used in rehabilitation systems generally.

**4.2.1.1 DC motors**

DC motor is an electric motor that it converts direct current electrical energy into mechanical energy. Rotary movements of dc motor are smooth, precise and powerful. Speed of motor is in directly proportional to applied voltage. Output torque of the motor is directly proportional to armature's windings current strength. Structure of the dc motor is shown below.

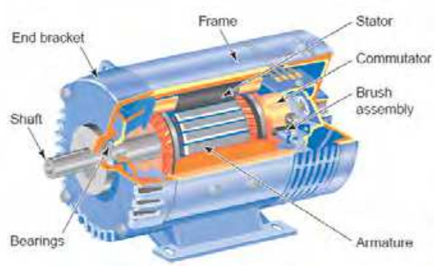



Fig. 5. Major Components of DC Motor (Petruzella, 2010)

As it is shown in the figure, dc motor contains electrical and mechanical components such as stator, armature, commutator, brushes, body and shaft.

DC motors are classified as brushed and brushless based on the presence of brushes in their structure. The induced current to the motor is transferred to the armature in two ways such as using brush and commutator or using electrical circuits. Brushed DC motor is a dc motor that it realizes commutation process with brushes and collectors. Brushed dc motors are classified as permanent magnet dc motors and electromagnet dc motors based on the source of the using magnetic field in their body. Permanent magnet dc motor use permanent magnets to produce stator's major magnetic field flux and use electro-magnets to produce armature's flux. Movement of the armature's magnetic field is obtained by the switching currents which flow in the armature's windings. Brushless DC motor hasn't collectors and brushes. Rotary parts of the motor consist of permanent magnets and stationary parts consist of miniature windings. The currents flow on the windings is controlled by the optical or magnetic sensors. This type of motor produces high torque.

DC motors are classified three types such as serial dc motors, shunt dc motors and compound dc motors based on the methods of excitation.

DC Motor is often use in rehabilitation robotics. It is used in applications not requiring high precision. For example LOKOMAT is a rehabilitation robot that it has four rotary joints. Stretching and expansion movements of the hip and knee are generated with these rotary joints. These movements of rotary joints are generated by dc motors. (Bernard et al., 2005)

MIME is a rehabilitation robot which uses PUMA 560 robot manipulator system to treat upper limbs of the patients. MIME use dc motors and gearboxes for positioning and orientation of end effector (gripper) of the robot (Lum et al., 1995, 1997).

#### 4.2.1.2 AC motors

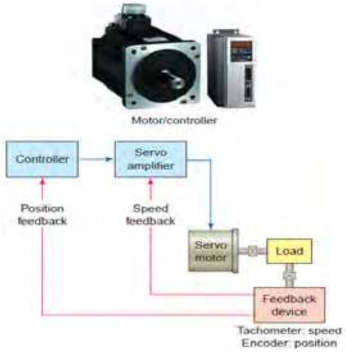
Ac motor is an electrical motor that converts alternative current electrical energy into mechanical energy. It is classified two major types such as induction motor and synchronous motor. Basic principle of these motors is that a mass is manufactured with magnetic plate is draft by rotary electromagnetic field.

Induction motor is preferred much than DC motor because of its cheapness and less maintenance requirement. Induction motor has stator, armature, body, supports and propeller. Armature windings are too much and stator's magnetic field induces current to armature. Armature doesn’t connect any other energy supply. Rotation speed of the induction motor is changed slightly by load and rotation speed is regulated step by step. Speed of armature is always less than speed of stator's magnetic field because of the load on the motor. Induction motors are divided two types accoording to count of phase such as single-phase and three-phase induction motors and are divided two types according to their structure such as squirrel-cage induction motors and wound-rotor induction motors.

Synchronous motor is an alternative current electrical machine which rotates constant speed in proportion to frequency and pole numbers. Magnetic field is generated by current which is supplied in armature windings. This magnetic field is constant. Thus rotary field speed and speed of armature are same for this motor. This motor is used for applications requiring high power. As a result of synchronous rotation of the motor, sliding doesn’t occur. Synchronous motors are classified two types based on the structure of armature such as salient pole synchronous motors and roundly pole synchronous motors.

#### 4.2.1.3 Servo motors

Servo motors are used very effectively in velocity and displacement control of electro mechanical applications. Servo motors (Fig 6.b) have continuous motion and used feedback signals for velocity and displacement control. In servo motors the position of rotor is feedback to the controller (Fig 6.a) so the position error is minimized. (Petruzella, 2010)




a. Closed loop systems of Servo motors

b. Servo Motor

Fig. 6. Closed loop systems of servo motors and servo motor (Petruzella, 2010)

In close loop servo-mechanism system as illustrated above position and velocity of motor measured with encoder and tachometer respectively and feedback to the controller and servo amplifier. Servo motors, unlike to the step motors, can be driven both AC and DC. Generally DC servo motors, AC servo motors and Brushless AC or DC motors are used in applications. DC servo motor design is similar to conventional DC motor design. A strong magnetic field is generated on DC servo motors to obtain high torque and excessive loadability. General properties of servo motors are; they need less energy according to conventional motors, they have small motor diameters with respect to standard DC motors, generated torque is proportional to rotor diameter and they have small inertia moments. DC servo motors are generally used in robotic applications that need high power. AC servomotors are of the two-phase squirrel-cage induction type motors. Main advantages of this type motors are, high safety, need less maintenance and not include commutators and disadvantages are; low efficiency, high heat dissipation and the requirement of AC square wave power source. In brushless DC servo motors rotor and stator is replaced. As a result of this brush and collector systems are cancelled and electro mechanical dissipations, which are based on friction and resistance between brush/collector systems, are disappearing. It is possible to obtain high torque from these motors. But the main disadvantage is a circuit must replace with collector, means that extra hardware requirement. Due to the precision of servo motor, they find spread place in robotic applications. Applications of servo motor in rehabilitation robots are explained in examples illustrated below.

Kikuchi et al., developed a rehabilitation system named Hybrid-PLEMO for it can be switched between active type and passive type and used with ER clutch/brake tool. They used AC servo motor and obtained two directional rotations with slow motions. They distribute these rotations on two ER tool. ER tool 1 is controlled the clockwise rotations and ER tool 2 is controlled the anti-clockwise rotations. (Kukichi & Furusho, 2009)

#### 4.2.1.4 Stepper motors

A stepper motor (Fig. 7) converts electronic pulse into proportionate mechanical movement. Stepping motors are attractive because they can be controlled directly by computers or microcontrollers. Motor's shaft rotation quantity is in direct proportional to pulse number and speed of the motor is in direct proportional to frequency of this pulse. Rotate angle of the motor per each pulse determine the resolution of the motor. Stepper motor is used for open loop control systems generally. Produced movement for each pulse is precise and repeatable. Thus stepper motor is used for load positioning systems effectively. Step motor produces less power than 1 hp.

Fig. 7. Stepper Motor (Petruzella, 2010)

Advantages of stepper motor are that it doesn't need feedback, any positioning error doesn’t occur during the motor movement and it doesn’t need maintenance because of its simple structure. Disadvantages of this motor are that its movement is not continuous, it is less powerful than other motors and it may cause positioning errors in open loop control of friction based load applications. Stepper motors are classified three types such as variable-reluctance stepper motors, permanent magnet stepper motors and hybrid stepper motors.

**4.2.1.5 Linear motors**

Linear actuator is an actuator that creates motion in straight line, as contrasted with circular motion of a conventional electric motor (Boldea & Nasar, 1997). Linear actuators are classified types such as mechanical linear actuators, hydraulic and pneumatic linear actuators, piezoelectric linear actuators, electro-mechanics linear actuators and telescoping linear actuators.

In industry linear motor is used for applications requiring long distance and high sensitivity. Linear motor converts electrical energy into linear mechanical movement. Linear motor has had its stator and rotor "unrolled" so that instead of producing a torque (rotation) it produces a linear force along its length. Many designs have been put forward for linear motors, falling into two major categories, low-acceleration and high-acceleration linear motors. Low-acceleration linear motors are suitable for maglev trains and other ground-based transportation applications. High-acceleration linear motors are normally rather short, and are designed to accelerate an object to a very high speed, for example see the railgun. The main advantages of any linear motor is that it totally eliminates the need cost and limitations of mechanical rotation-to-translation mechanism. Thus the complexity of the mechanical system is drastically reduced. (http://www.dynamicdevices.com, December 2011). Its other advantages are that it works high speeds and high accurate, it response faster than mechanical transmission and there is no mechanical linkage in linear motor thus the stiffness of the motor increase. Disadvantages of this motor are that its performance is are affected by the temperature directly, it need an interface unit to connect the machine control component of the system.

Zhang use a linear motor in his rehabilitation robot in medical practice is to recover the function of the motor system of the injured limbs and trunk. His motor system issues break into two distinct categories: one is related to biomechanical/biophysical applications and the other to motor learning. Motion-speed and motion-range of a limb is limited by injury, burns, or postoperative conditions in that skin, ligaments, and muscles are inelastic from scar tissue. There are two modules in the Continuous Passive Motion Motion (CPM) mechanism for index fingers: biomimetic finger module and biomimetic muscle module. The two modules are linked by biomimetic muscle. The CPM mechanism can be driven from long-distance with the biomimetic muscles. Thus the biomimetic muscle consists of two pulleys, four spring bushings, two springs, a cord and a linear motor. The transmission distance between the linear motor and the CPM mechanism is adjustable by regulating the length of springs and cords. (Fuxiang, 2007)

### 4.2.2 Hydraulic and pneumatic actuators

#### 4.2.2.1 Hydraulic actuators

Hydraulic systems (Fig. 8) are designed for moving heavy loads with high pressurized fluid in pipes and pistons which controlled with mechanical or electro mechanical valves. The figure shown above illustrates a hydraulic system and its' the components. A hydraulic system consist a tank, hydraulic pump, pressure regulator, valves and pistons. Tank is the storage member of the hydraulic fluid.  Hydraulic pumps are generally drived by electric motors. At first, pressurized fluid is adjusted in pressure regulator for the hydraulic system. Regularized fluid is canalized by valves and actuated the hydraulic piston by this way linear motion is obtained. Most common hydraulic actuators are pistons and hydraulic motors. There are two types of piston used, one is single acting and the other is double acting, and hydraulic motors can be classified as gear motor, gerotor motor, and radial piston motor. Hydraulic actuators have great advantages like; have large lifting capacity, can used with servo control, have quick reaction capability, have self-cooling, have smooth motions at low speeds. But hydraulic systems are expensive, not appropriate for circular motion at high speeds and it is difficult diminish the extent of the system.

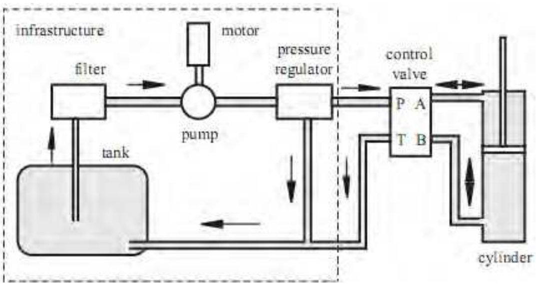



Fig. 8. Major Components of Hydraulic System

#### 4.2.2.2 Pneumatics actuators

Pneumatic systems are moved with high pressurized gas in pipes and pistons which controlled with mechanical or electro mechanical valves. Pneumatic system consists of compressor, air conditioner unit and reservoir for gas storage, valves and piston. Working principle for pneumatic systems is similar to the hydraulic systems. One significant difference is pneumatic systems used compressible gas. Most common pneumatic actuators are pistons.

General advantages of pneumatic actuators are cheap, quick, and clean and safety on the other hand, desensitisation because of the gas compression, noise pollution because of the exhaust, gas leaks, needs extra drying and filtering and it is difficult to speed control. The disadvantage of pneumatic systems is that control of the pneumatic actuators is very difficult so their usage in rehabilitation robots is restricted. Some of the publications in this subject summarized below.

In their study Klute et al. use pneumatic muscles for bottom knee prosthesis. It aims to bring into connection between force, length, speed and activation with the myo-tendinous actuator and in this actuator flexible pneumatic muscles, hydraulic dampers and springs are used. (Klute et al., 1999)

Girone at al. design a Stewart platform-type haptic interface to use in rehabilitation systems. The system supplies six-DOF resistive forces in response to virtual reaility-based exercises running on a host PC. The used Stewart platform has double acting pneumatic cylinders, linear potentiometers as position sensors and six-DOF force sensor. (Girone et al., 2001)

### 4.3 Sensors in rehabilitation

We can examine sensors in two classes: mechanical and biological sensor.

#### 4.3.1 Mechanical sensors

**Force sensor:** A Force Sensor is defined as a transducer that converts an input mechanical force into an electrical output signal. Force Sensors are known as Force Transducers, as well. Force sensor can measure forces in three axes. The device that is measure in single axis is called as "load cell". Force sensors are usually used for measuring applied or reaction force. Prostheses, therapeutic exercise robots and exoskeletal robot manipulator are common application area of force sensors in rehabilitation.

**Position sensors:** A position sensor is a device which allows position measurement. Position sensors can be either linear or angular. It is also known as potentiometer, rotary encoder or displacements sensor. Generally, it is used in mechanical systems for position feedback.

**Goniometers:** Goniometers are used to measure joint angle in rehabilitation. First and still used goniometers are mechanical. However, new types of electronic goniometers have been used in medical centres.

**Hand Dynamometers:** Hand Dynamometer is used to measure gross isometric power grip force.

**Eye tracker:** Eye tracker is a device that measures eye positions and eye movement. Eye trackers are especially used by disabled people to control a wheelchair.

#### 4.3.2 Biological sensors

**EMG system and sensors:** The electromyogram (EMG) is an electrical response of the contracting muscle. Since their amplitude is quite small EMG signals are complicated. This is why EMG signals must be processed through signal analysis methods. In rehabilitation, EMG signals are used for two purposes, to evaluate patient muscle performance and to control a mechanical system such as a robot or prostheses.

**EEG system and sensors:** The electroencephalogram (EEG) is electrical activity of the brain. EEG recordings are obtained by placing electrodes of high conductivity in different locations of the head. Measures of the electric potentials are recorded between a pairs of active electrodes (bipolar recordings) or with respect to a supposed passive electrode called reference (monopolar recordings) as in EMG (Quiroga, 1998). Evaluating of EEG is harder than EEG. At the present time, many research studies have been done about that.

## 5. Rehabilitation robots

### 5.1 Assistive rehabilitation robotics

Robotic systems supporting daily tasks of patient such as holding, lifting, moving, free mobility are called as *assistive robotics*. Assistive robotics systems are developed in order to support disabled people to continue their life without any help from others.

There are some problems in the course of producing such technologies:

- Their high costs
- customized design requirements
- Robotic system can need many sensors according to disability level. This situation requires developing and using of high-performance computers, complex control methods and softwares.
- If patient cognitive capacity is not enough to use robotic system, patient could have difficulties in operating these systems. In this situation, safety problems can occur.

Target group of assistive robotics generally consist of people whose manipulation skills damaged, muscular dystrophy, cerebral palsy children, spinal cord injury. In particular, this robotic area that is related to daily life and individual is drawn attention with increasing population. On the other hand, its market share gains momentum day by day.

Mechanism and user interface design is very important in assisitve robotic systems. Interface is called as human-machine interface, human-computer interface and human-robot interface in the literature. Challenges of design of mechanism and user interface are as follows:

- Operator of system is not a specialist or engineer.
- Operator has some physical disables. Therefore, it needs a design that can enable to communicate between patient and system.
- Profiles and level of disabled is different. That is why; it needs to develop designs which can respond to needs of a wide-spectrum of disabled people and individuals.

It is required easy-to-use interfaces which provide interaction with system and useful mechanism in order to solve these problems. (Hammel, 1995)

The user interfaces are supported with several adaptive hardwares and sofwares such as speech recognition systems, track balls, special keyboard, eye-trackers- motion sensors etc.

Briefly a powerful user interface has features as summarized below:

- Individual
- Functional

- Adaptation capability
- Easy-to-use and understandable
- Funny

Assistive robotics can be detected in three groups: manipulation aid, mobility aid and social aid.

### 5.1.1 Manipulation aid

There are many studies have been done about manipulation aid robotic. Some of them are given follows:

**ProVAR** (Professional Vocational Assistant Robot)**:**

The ProVAR robotic system is an assistive robot for individuals with a severe physical disability. It allows that a patient can control the system through a direct manipulation The ProVAR system has a PUMA-260 manipulator mounted on an overhead (see Fig 9). An optical emitter / detector, a force sensor and proximity sensors are integrated to the system in order to control the system and improve safety. Patient controls the system through a computer which has Windows-NT operating system. Computer also communicates with office devices such as telephone, fax and internet devices. (Van der Loss et al., 1999)

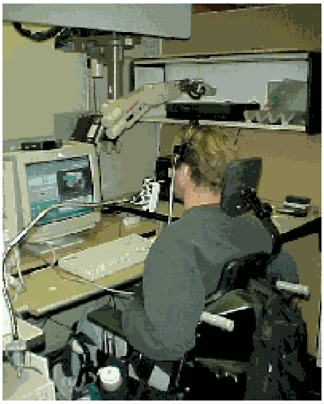


Fig. 9. ProVAR

**AFMASTER:** This robot was developed as a work station and works in 2m*3m area. The robot services goods which are in its office via user commands. AFMASTER allows severely disabled people to get back to work by automatic manipulation facilities. (Gelin et al., 2001)

**DeVAR III – ADL:**

DeVAR system includes a PUMA-260 industrial robotic arm, a computer and a wheelchair. End effector of robot manipulator is Otto Bock Greifer prosthetic hand. This hand can realize fingertip, cylindrical, and hook grasps. User uses the system via voice commands. The robot arm is surrounded by daily living equipment such as a microwave oven, a refrigerator, a tool holder for an electric shaver, a spoon, an electric toothbrush, pump toothpaste, adapted wash/dry cloths, and a mouth stick. Voice commands operate an X-10 environmental controller which supplies power to the robotic workstation, computers, lights, radio, and other appliances. (Hammel et al., 1987)

**HANDY-1:**

The Handy 1 is a rehabilitation robot designed to provide people with severe disability to gain/regain independence in important daily living activities such as: eating, drinking, washing, shaving, teeth cleaning and applying make-up. It has a robotic manipulator that has three degree of freedom. (Topping, 2002)

Fig. 10. Handy 1

### 5.1.2 Mobility aid

Mobility of disabled people in their houses and external environment is a very important phenomenon. To this regard, safe and reliable mobile robotic assistive devices are needed. These types of robots must be intelligent control structure. A state of art robotic device designed for mobility is able to:

- perform automated navigation tasks/behaviors through sensors,
- provide to access to users who may lack fine motor control,
- realize gesture recognition,
- recognize voice command
- do vision-based interaction,
- have ability to drive on all terrains such as stairs, curbs
- be adapted to intelligent homes, buildings communicate with smart wheelchairs
- Extend to other assistive devices (e.g. scooters)

To achieve these specifications sensors and software must be very powerful and control method of wheelchair must be flexible and effective. On the other hand, user interface between wheelchair and patient must be user-friendly.

Different input commands can be used in order to control a wheelchair. Traditional methods are joysticks, pneumatic switches and so on. Recently, hand voice recognition, eye tacking and machine vision techniques have been started to use on smart wheelchairs.

A wheelchair needs clear and correct information to perceive its surrounding. Therefore, sensors have a key role to control a wheelchair. Sonar sensors, infrared range finder, laser range finders, laser strips and cameras are being frequently used. Since their size and price sonar and infrared sensors are often used in most applications. However, they are not well suited to identify drop-offs such as stairs, cubs etc. That is why, laser rage finders are used. More accurate obstacle ad drop-off detection can be realized using them. On the other hand this type of sensors is very expensive and large. Mounting of them to a wheelchair is not easy. Laser striper consists of a laser emitter and a-charge coupled device camera. The laser striper cheaper than laser range finder but it can read false because of environment conditions. That is why, it has not been preferred. Briefly, a sensor must be cheap, accurate, small, lightweight, and must be not affected from environmental conditions such as temperature, lighting. On the other hand it has low energy consumption and can easily be mounted.

Researchers have developed different type of control methods and software. Some of them used artificial intelligence techniques whereas others multilayered control techniques including sensor - reactive behaviors.

Smart wheelchairs have several types of operating modes. a) Autonomous navigation with obstacle avoidance mode: wheelchair travels from its current positions to given positions b) Wall following mode: Operator controls wheelchair. Wheelchair avoids or stops in front of obstacle c) Door passage mode: Wheelchair passes from door with traverse movement d) Docking mode: Wheelchair enables close approach to object. e) Reverse trajectory: Wheelchair returns it's starting positions using recorded travel trajectory f) Target tracking mode: Wheelchair can follow and navigate an object g) Line following mode: Wheelchair can follow a line that was marked in environment. (Simpson, 2005)

There are some challenges faced by robotic device designed for mobility. Human intention and adapting it for a robotic device is not so easy. On the other hand, if users of device have a motor control problem this process will be harder. In terms of technology, designing of flexible input devices has a curious problem and cost of individual-oriented design can be high. Some well-designed mobility aid robotic device given is as follows:

**PALMA:** (assistive platform for alternative mobility)

PALMA is a robotic device to assist the mobility of children affected by CP (Fig 11). The PALMA has an open, safety and flexible structure; it can be adapted to different pathologies and varied motor dexterity. It allows to user a safe navigation using simple obstacle avoidance strategies. Especially, ultrasonic sensors were used for detection. In order to control the detection unit a PIC 16C73 microcontroller was used. Children can interact with environment via PALMA. (Ceres et al., 2005)

**PAMM: (Personal Aid for Mobility and Monitoring)**

PAMM is designed to assist the elderly people living independently (Fig. 12). It provides physical support and guidance, and it can monitor the user's basic vital signs. The PAMM has a force-torque sensor mounted under the user's handle to sense the user's intent. The system is controlled by an admittance based controller. It can communicate with a computer via wireless network in order to receive up- dated planning information and to provide information on the health and location of the user. (Dubowsky et al., 2000)


Fig. 11. PALMA (Ceres et al., 2005)

Fig. 12. PAMM (http://robots.mit.edu)

**MAID (Mobility Aid for Elderly and Disabled People)**

MAID is a smart wheel chair (Fig. 13). It is based on a commercial wheelchair that has been equipped with an intelligent control and navigation system. It allows using narrow and wide area. MAID can detect the environment objects as well as to identify which object is stationary and which is moving. Thus it can easily be used in crowded area. (Prassler et al., 2001)

**Hong-Kong Advanced Robotic Lab. Smart Wheelchair:**

A smart wheel chair was developed by the Chinese University of Hong-Kong Advanced Robotic Lab. This wheelchair has a human friendly interface for high-level control, and uses human skill models to significantly enhance the usability and functionality of traditional electric wheelchairs. To this regard a neural network structure was developed to map sensor readings to control actions to play back taught routes. (Hon Nin Chow & Yangsheng, 2006)

Fig. 13. MAID

Fig. 14. Smart wheelchair

### 5.1.3 Exoskeletal robot manipulators: (ExRM)

Exoskelelatal robot manipulators are used to provide or assist human motions. ExRM has a mechanism structure showing compliance with human joints and limbs. It supports human motions via actuators positioned in robot joints. ExRMs have been developed for industrial or military purposes. However, recent years research studies for which supporting physically disabled people movements about Ex RM have gained momentum. An ExRM interacts with a person directly. Therefore, control via biological signal processing stands out in these systems. On the other hand, it needs control structure based on artificial intelligence.

First studies have been started in 1960s. First ExRM was developed by Hardiman. Hardiman project aimed to increase human power on aircraft carriers, in underwater construction and on missions in outer space (Mosher, 1967)

Today research studies about usage of ExRM in rehabilitation area are being realized. A useful ExRM has features which are given below:

- Compatible with user's biomechanical features
- Safe
- Effective motion transfer
- Low power consumption
- Easy chargeable battery
- High performance control method
- High performance signal processing
- Small size powerful actuators

ExRMs can be classified three groups, lower extremity, upper extremity and full body systems. In these systems, electrical motors are generally used as actuators. On the other hand, in some studies pneumatic and hydraulic systems are used, as well. Rehabilitation purposed ExRMs studies are presented follows.

Fig. 15. (Moubarak et al., 2009)

Moubarak and *et al.* designed an ExRM for upper limb rehabilitation (Fig 15). The robot can perform repetitive exercise motions without physiotherapist. It has 4 DOF for shoulder, and elbow motions. Basic control method of system is force control. In particular, lightweight of mechanism was taken into account during design of the robotic mechanism. Servo motors were used as actuator. (Moubarak et al., 2009)

Fig. 16. ExRm of Tsai and et al. (Tsai et al. 2010)

Tsai et al. designed a 6DOF ExRM for passive and active exercises of upper limbs (Fig 16). Patient motion intension was sensed with EMG and force feedback combination. PID and impedance control methods were used to control of the system. Links are actuated with DC motors. (Tsai et al., 2010)

Fig. 17. Rosen and et al.'s 7DOF Manipulator EXO-7 (Perry, 2007; Yu & Rosen, 2010)

Yu and Rosen designed an anthropomorphic 7DOF Exrm (EXO-7) in order to assist shoulder, elbow and wrist motions (Fig 17). There is no backlash on the EXO-7. Its mechanical specifications are excellent. Therefore user can insert his arm easily to manipulator. It can be used for a therapeutic and diagnostics device for physiotherapy, an assistive (orthotic) device for human power amplifications, a haptic device in virtual reality simulation, and a master device for teleoperation. However, researchers used a new PID controller to guarantee the asymptotic stability in their last study. (Perry, 2007; Yu & Rosen, 2010)

Fig. 18. ARMin (Mihelj et al., 2007)

ARMin is a 7DOF Exrm which has backdrivable DC motors and position-force sensors (Fig 18). It was used for training of patient for daily life activities. It uses admittance and impedance control methods which is best-known control methods in rehabilitation area. As all drives are backdrivable, a therapist can control the ARMin manually if it is necessary. (Mihelj et al., 2007)

Fig. 19. (Yamura et al., 2009)

Yamaura and et *al.* developed a hand rehabilitation system. It consists of two units rehabilitation mechanism that moves fingers with actuators and a data glove that control the mechanism. The mechanism is wire-driven and all three joints of finger can be controlled with it (Fig 19) (Yamura et al., 2009)

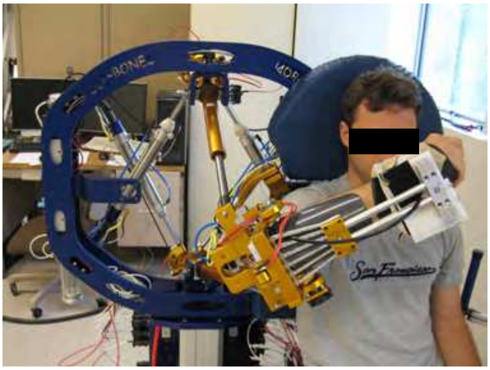


Fig. 20. Bones (Klein et al., 2008)

**BONES** (Biomimetic Orthosis for the Neurorehabilitation of the Elbow and Shoulder) is a 4DOF Exo-RM (Fig 20). It can perform arm internal/external rotation without any circular bearing element. This system uses pneumatic actuators. BONES is able to imitate a wide range of motion of the human arm. (Klein et al., 2008)

Fig. 21. SUEFUL-7 (http://www.me.saga-u.ac.jp/~kiguchi/research_en.html#research01, December 2011)

SUEFUL-7 (see Fig.21) is an EMG signal based 7DOF ExRM developed by Saga University. It can assist the motions of shoulder vertical and horizontal flexion/extension, shoulder internal/external rotation, elbow flexion/extension, forearm supination/pronation, wrist flexion/extension, and wrist radial/ulnar deviation. On the other hand researchers used a combination of impedance control method and muscle model oriented control in order to control of robot. Impedance parameters were adjusted through considering of upper limb posture and muscular contraction level. (Gopura et al., 2009)

### 5.1.4 Social assistive robotics

Social assistive robots help people by non-physical social interaction. The aim of social assistive robotics is to success purposes of rehabilitation and patient training. The robot interacts with stroke patient as therapeutic during daily life activities such as putting magazines to shelf.

## 5.2 Prostheses

Prosthesis is a mechanism which is developed in order to continue daily life activities of amputee people without others. Lower limb prostheses (Fig 22) are important in terms of providing mobility of person. However, people use their upper extremities much more for daily tasks such as lifting, pushing, gripping. That is why; one can find more about upper extremity prostheses.

Fig. 22. Lower limb prosthetic (http://www.robaid.com)

Currently, myoelectric controlled prostheses are frequently used and reach studies which is related to this subject are being continued. The first study about prosthesis was realized by German physicist Reinhold Zeiter. Several studies about that were done in some countries such as Japan, USA and Rusia until 1960s. The myoelectric prosthesis called as MYOMOT which was developed by Otto Bock and Viennatone Comp. (Austrian manufacturer of hearing device) is regarded as the cornerstone in 1964 . (Inal, 2000)

There are some important challenges in producing prostheses:

- To control and coordinate multiple joints of a robotic limb
- To reach a high capability for a robot manipulator in terms of sufficient range of force, acceptable weight, portable power source and necessary sensors.

Useful, efficient and a high-technological prosthesis should have:

- Sufficient degree of freedom
- Resistant to environmental influences
- Sensitive artificial sensors,
- Well-designed cybernetic interface,
- Light and strong actuators,
- Long-life and forceful power source,

### 5.3 Therapeutic exercise robots

In general, a person with movement disabilities due to arm or leg problems needs to undergo periods of physiotherapy sessions spread over a long period of time. The sessions comprise a series of repeated and routine physical movements with the assistance and under the observation of a physiotherapist (PT). Transporting the patient to the medical center or calling a PT to where the patient is located are factors that further increase the cost of this process. The process of strengthening muscles to their normal values is costly and requires time and patience. Some important reasons for the utilization of robots in rehabilitation can be listed as follows; (Krebs, 2006)

- Robots easily fulfill the requirements of cyclic movements in rehabilitation;
- Robots have better control over introduced forces;
- They can accurately reproduce required forces in repetitive exercises;
- Robots can be more precise regarding required therapy conditions.

Because of these reasons, the number of studies about the usage of robots in rehabilitation has increased, especially in the last ten years.

During the rehabilitation process, patients sometimes move their extremities suddenly due to reflexes. Conventional machines such as CPMs do not respond in these kinds of situations and are hence not suitable for physical therapy. If a reflex causes a patient's leg to move while the machine is operating, an improper load results and can damage the patient's muscle or tendon tissue. (Sakaki et al., 1999) Because of this, there is a need for therapeutic exercise robots which can accomplish the rehabilitation of extremities based on the patient's complaints and real-time feedback during rehabilitation processes. Therapeutic exercise robots can be classified in two groups, upper limb and lower limb rehabilitation robots.

**Therapeutic exercise robot systems for upper limbs:**

Lee and others developed a robotic system for the rehabilitation of upper limbs of paralyzed patients using an expert system (Lee et al., 1990). This system combines the needed skills of therapists with a sensor-integrated orthosis and a real-time graphics system to ensure proper interaction and cooperation with the patient in order to achieve the goals of therapy. It can achieve passive exercises, motor-learning training and tone reduction.

Lum and *et al.* developed a prototype device called MIME (Mirror Image Motion Enabler) that implements passive and active assistive movements for upper extremities (Lum et al., 1995, 1997). This system uses two commercial robots (Fig 23).

Fig. 23. MIME

Another system developed for rehabilitation of upper extremities is a robot manipulator with 5-DOF (degrees of freedom) called MULOS (https://www.asel.udel.edu, August 2008). It is used as an assistive device and to perform passive and resistive exercises. (See Fig 24)

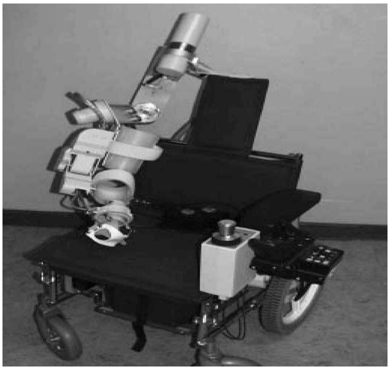


Fig. 24. MULOS (Johnson et al., 2001)

Krebs and others developed and have been clinically evaluating a robot-aided neurorehabilitation system called MIT-MANUS (Fig. 25) (Krebs et al., 1998, 2003). This device provides multiple degrees of freedom exercises of upper extremities for stroke patients. This study showed the effect of robot-aided rehabilitation.

Fig. 25. MIT-Manus (http://coobox.wordpress.com)

Rao and others introduced another system using a Puma 240 robot for passive and active rehabilitation of upper extremities (Rao et al., 1999). In the passive mode, the robot moves the subject's arm through specified paths. In the active mode, a subject guides the robot along a predefined path, overcoming specified joint stiffness.

Richardson and et al. developed a 3-DOF pneumatic device (Fig.26) for the rehabilitation of upper extremities using PD control and impedance control methodologies (Richardson et al., 2003, 2005).

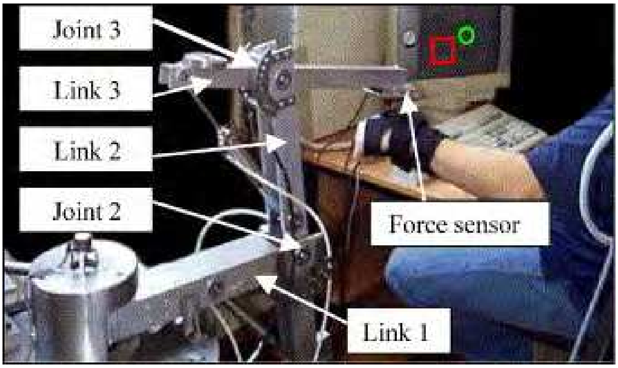



Fig. 26. 3-DOF pneumatic actuated device. (Richardson et al., 2003)

Another study for the rehabilitation of upper extremities is the REHAROB project, which uses industrial robots (Fig.27) (http://www.rehab.manuf.bme.hu, July 2008). A database is formed with the necessary force and position produced by the sensors placed on the patients during the rehabilitation process. Industrial robots then repeat the same procedure using this database.


Fig. 27. REHAROB

Reinkensmeyer and others developed a 3-DOF system called ARM Guide (Assisted Rehabilitation and Measurement Guide) for the rehabilitation of upper extremities (Reinkensmeyer et al., 2000). The ARM Guide (Fig. 28) can diagnose and treat arm movement impairment following stroke and other brain injuries. As a diagnostic tool, it provides a basis for the evaluation of several key motor impairments, including abnormal tone, incoordination, and weakness. As a therapeutic tool, the device provides a means to implement and evaluate active assistive therapy for the arm.

Fig. 28. ARM Guide

A 3-DOF system, called GENTLE/s (Fig.29), was developed for the rehabilitation of upper extremities using a haptic device and the virtual reality technique, controlled by the admittance control method (Luieiro et al. 2003).

Fig. 29. GENTLE/s (Amirabdollahian et al., 2007)

**Therapeutic exercise robot systems for lower limbs:**

LOKOMAT (Bernhardt et al., 2005) and ALEX (Banala et al., 2007) were developed as gait rehabilitation robotic systems. The robotic systems for therapeutic exercises for lower limbs were developed to perform some repetitive, resistive, and assistive exercises which are performed by the PT or equipment.

Okada et al. employed an impedance control methodology in a 2-DOF robotic system (Fig.30), where the position and force data are received and recorded for the robotic system to imitate the corresponding motion (Okada et al., 2000)

Fig. 30. TEM: Therapeutic Exercise Machine

Bradley et al. developed a 2-DOF autonomous system called NeXOS (Bradley et al., 2009) that is able to perform active assistive, passive and resistive exercises using pre-training visual position information. It can be used for knee and hip extension-flexion movements.

Moughamir et al. devised a training system called Multi-Iso (Moughamir et al., 2002). This system is also able to perform assistive, resistive and passive exercises like NeXOS. This 1-DOF system is used for knee limb and extension-flexion movements. Multi-Iso (Fig.31) uses classical force, position and speed control methods developed with fuzzy control techniques.

Fig. 31. Multi-ISO

Many of the developed therapeutic robotic systems are designed for only assistive or only passive and resistive exercises. Furthermore, few studies aim to model the PT's manual exercise and directly convey the PT's rehabilitation capability to the patient (http://www.rehab.manuf.bme.hu, July 2008; Okada et al., 2000; Akdogan et al., 2011)

Akdogan, Adli and Tacgin developed a 3DOF robot -Physiotherabot- for lower limb rehabilitation (Akdogan et al., 2009, 2011). Physiotherabot (Fig.32) can perform all active and resistive therapeutic exercises in addition to manual exercises of the PT for lower limbs. Meanly, it can work not only as a physiotherapy machine but also as a human (PT). On the other hand, Physiotherabot has 3-DOF and can perform flexion – the extension movement of the knee and hip, and the abduction-adduction movement of the hip.


Fig. 32. Physiotherabot

### 5.4 Cognitive robotics

Cognitive aid robots are very different from other types of therapy robots because they are actually agents of the therapist. They are not necessarily attached to the person who is getting physical therapy. For cognitive aid robots, also called communication aid robots, the goal is to provide a safe and friendly environment for the child to interact with other children or just to play in fact. The robots of this category are mostly focused on children who have cerebral palsy or children who have autism (Van der Loos, ND). There are many cognitive robots. Some of them given as follow:

Fig. 33. Cognitive robot CosmoBOT (http://www.anthrotronix.com, 2011)

Cosmo Bot (Fig.33) was developed to motivate children to participate more fully in therapy and education. CosmoBot was tested with children. Especially, it can be used for Downs Syndrome, cerebral palsy, muscular dystrophy, apraxia, neurodevelopmental disorders, and language developmental disorders. CosmoBot is a robot with nine degrees of freedom. It can be operated via computer-based software, and children can operate CosmoBot by using some input devices. (http://www.anthrotronix.com)

**KASPAR (Kinesic and synchronisation in personal assistant robotics):** KASPAR (Fig.34) is a child-sized humanoid robot developed by University of Hertfordshire. KASPAR is being used to study human-robot interaction that aims to build an open-source robot platform for cognitive development research. It was developed for robot assisted play for children with autism. KASPAR has 8 degrees of freedom in the head and neck and 6 in the arms and hands. It can open its mouth and smile. It can interact with children with its tactile sensors which is placed its skin surface. (http://kaspar.stca.herts.ac.uk)

Fig. 34. KASPAR

Another type of cognitive robots is pet robots. They communicate and interact with human. This interaction can be physically. They imitate animal reactions. The main purpose of pet robots is to support children and elderly people who need emotional and mental impairment using their imitation capability. They have several types of sensors such as visional, audial and tactile and have learning abilities for imitate emotions via interaction with human (Vander Loos; http:// www.aist.go.jp). There are many research studies about pet robots. In particular, **Paro Therapeutic robot** (Fig.35) is one of the best known. It allows the documented benefits of animal therapy to be administered to patients in environments such as hospitals and extended care facilities where live animals present treatment or logistical difficulties. It can reduce patient stress and their caregivers, stimulates interaction between patients and caregivers, and improves patient relaxation, motivation and socialization of patients. Paro has five kinds of sensors: tactile, light, audition, temperature, and posture sensors and 32-bit RISC processors. Moreover, it can understand light and dark. He feels being stroked and beaten by tactile sensor, or being held by the posture sensor. Paro can recognize the direction of voice and words such as its name, greetings, and praise with its audio sensor, as well (http://www.parorobots.com, 2011).

Fig. 35. Paro Therapeutic Robot (http://www.parorobots.com, 2011)

**Keepon** (Fig.36)**,** is another example about pet robots developed by Michalowski, Mellon and Kozima. It has two video cameras (eyes) and a microphone (nose) as sensors, and four motors. It can remotely be control by a therapist in another room. Furthermore, it can be operated in an autonomous mode, bouncing along to music or sounds. Therefore, monitor, track, and record of the children's improvement can be record that it is very important to rehabilitation. (Michalowski et al., 2009)

Fig. 36. Keepon (Michalowski et al., 2009)

## 6. Future of rehabilitation robotics

Looking at the world's population developments in the field of rehabilitation robots will continue. Other factors which affect developments in this area are given follows:

- Hardware & Software
- Sensors
- Wireless communication
- “Always-on” computing

It is expected that the infrastructure of hardware and software will develop, high speed internet connection will spread and real time application performance will increase. On the other hand more stable, unaffected from environmental factors, high performance, small size and cheaper sensor will provide this development. Developing wireless communication systems, more portable devices and using them in home will have impact on the area of rehabilitation robot, as well. Patients are observed by rehabilitation team through "everywhere and everytime therapy" concept. Patients' treatment process is maintained through remote control applications and device without coming hospital.

So, patient, his/her relatives and health care personal will have more effective treatment period. Patients will be treated faster and they will contribute to their community as social and economic.

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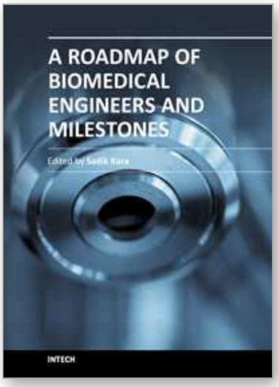


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