Al-Mustaqbal University

Biomedical Engineering Department

Class: 3rd

Subject: Rehabilitation Science and Engineering.

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2nd term – Lect. 5: Rehabilitation Robotics.

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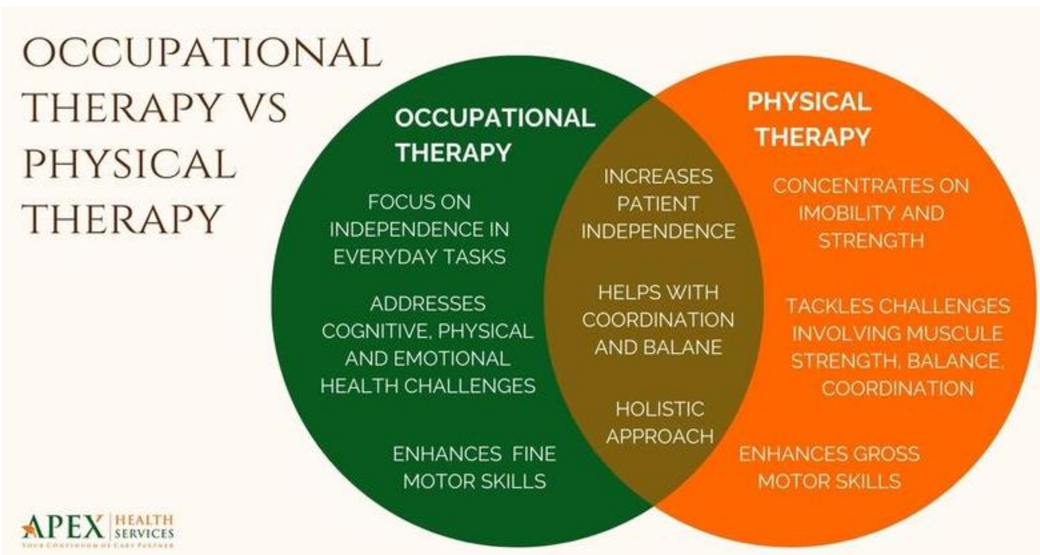
Need and Motivation (Demographic Shifts)

- **The Aging Population:** By the year 2050, 16.7% of the world's population (approximately 1.6 billion people) will be 65 years and older.
- In high-income countries like the United States, this percentage will reach 22% (88 million people).
- A rising number of elderly people correlates directly with an increased prevalence of risk factors leading to adult disability.
- For instance, the incidence of stroke increases as we age; it is the leading cause of serious long-term disability, with approximately 25.7 million people living with stroke effects worldwide.

Need and Motivation (The Healthcare Gap)

- The projected number of physicians and rehabilitation clinical providers will be severely inadequate to meet growing rehabilitation needs.
- In the United States, there is currently a ratio of only 1.29 Occupational Therapists and 3.62 Physical Therapists per 100 stroke patients.
- These disparities are significantly worse in low- and middle-income countries, where ratios may range from 0 to 0.01 clinicians per 100 stroke patients.
- Rehabilitation robotics technologies aim to bridge these healthcare gaps by supplementing the shortage of trained rehabilitation staff and increasing patient access to high-intensity therapy.

Need and Motivation (The Healthcare Gap)



Defining Rehabilitation Robots

- **The General Robot Definition:** An intelligent, computer-based mechanical system that can sense, think, and act to assist humans.
- **Rehabilitation Robot Definition:** A reprogrammable, intelligent, multifunctional machine designed to function in an assistive or therapeutic capacity to aid persons with disabilities or diminished functional capacity.
- **"Sensing and Thinking":** The robot processes sensor inputs from the environment and sends them to its microprocessors, which decide on a course of action.
- **"Acting":** The action could manifest as the robot's body moving across the room or the robot's arm moving an attached limb or joint along a path.

Target Populations (Stroke, TBI, & SCI)

- **Stroke:** Occurs when blood flow to the brain is blocked (ischemic) or leaks (hemorrhagic), causing brain cells to die from oxygen deprivation.
- **TBI (Traumatic Brain Injury):** Caused by a bump, blow, or jolt to the head. Approximately 69 million individuals sustain a TBI worldwide each year.
- **SCI (Spinal Cord Injury):** Impacts the vertebral column, disrupting signals between the body and the brain. An SCI can be complete (resulting in paralysis) or incomplete (some movement/sensation remains).

Target Populations (Neurological & Aging)

- **Parkinson's Disease:** A movement disorder occurring when brain nerve cells do not produce enough dopamine.
- **MS (Multiple Sclerosis):** A nervous system disorder that damages the myelin sheath protecting nerve cells.
- **CP (Cerebral Palsy):** A group of neurological disorders appearing in infancy/early childhood affecting body movement and muscle coordination.
- **Elders:** Older adults become vulnerable to age-related disabilities such as generalized weakness, cognitive changes, falls, and fatigue.

Introduction to Therapy Robots

- Technology-assisted therapy focuses on three key design features:

1. **Deliver:** Provide autonomous or semi-autonomous therapy to the body.
2. **Assess:** Measure the level of disability and impairment.
3. **Adapt:** Be adaptive to support the motor recovery induced during training.

- When coupled with imaging modalities such as CT or MRI ,evidence of training-induced brain reorganization (neuroplasticity) can be observed.
- Engineers manipulate parameters such as assistive/resistive forces and sensory feedback to influence therapy intensity and patient engagement.

Classification of Therapy Robots & Forward Kinematics

- **Control Mechanisms:**

➢ Active Systems: Have an actuator (motor) to actively assist or resist an impaired limb.

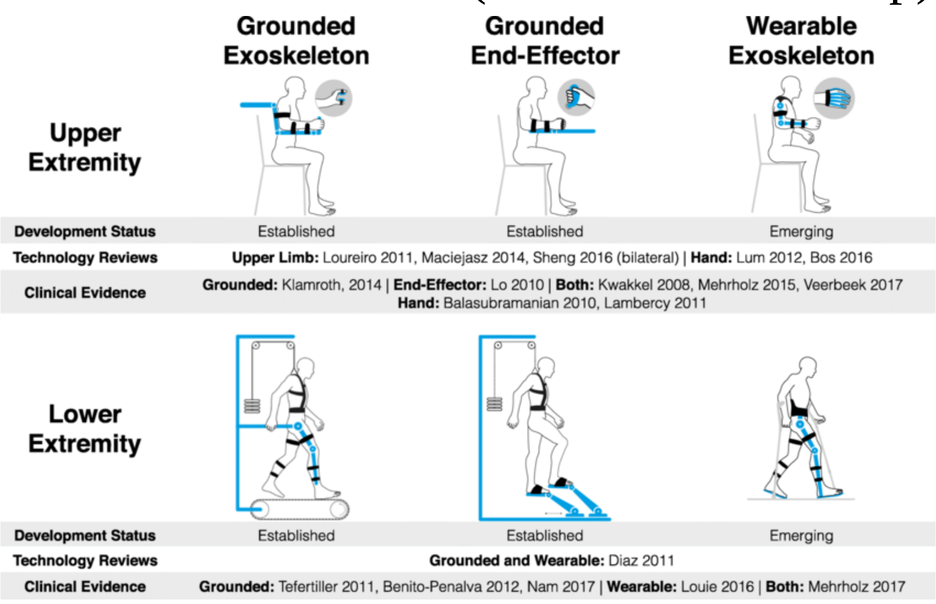
➢ Passive Systems: Offer non-powered assistance using elastic bands or springs.

- **User Interfaces:**

➢ End-Effector Robots: Attached to the user's hand, forearm, or leg at a single point of contact; they do not control movement at individual joints.

➢ Exoskeletal Robots: "Wearable" devices that typically have separate torque control applied to each individual joint.

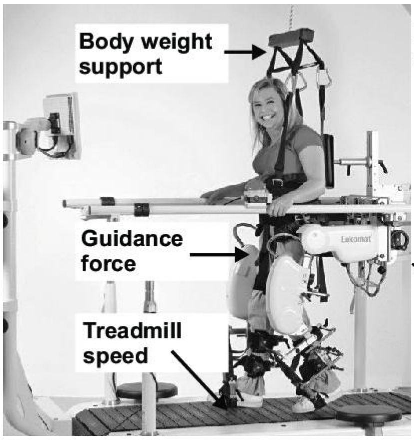
Need and Motivation (The Healthcare Gap)

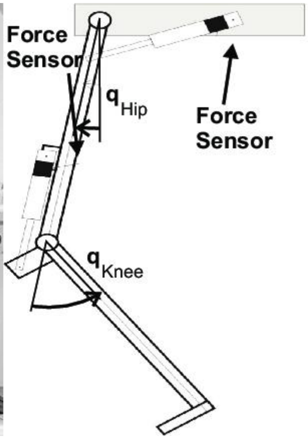


Lower Limb Therapy Robots (Treadmill-Based)

- The goal of lower limb therapy robots is to assist patients in the recovery of gait (walking) while reducing the physical burden and fatigue on human therapists.
- **Lokomat:** An exoskeletal gait training robot featuring two exoskeleton legs with 2 DOF each (moving the knee and hip joints). Patients are suspended over a treadmill via an overhead harness that provides body weight support.
- **Gait Trainer GTII:** An end-effector gait training robot that contacts the patient only at the soles of the feet and adaptively supports body weight.

Lokomat



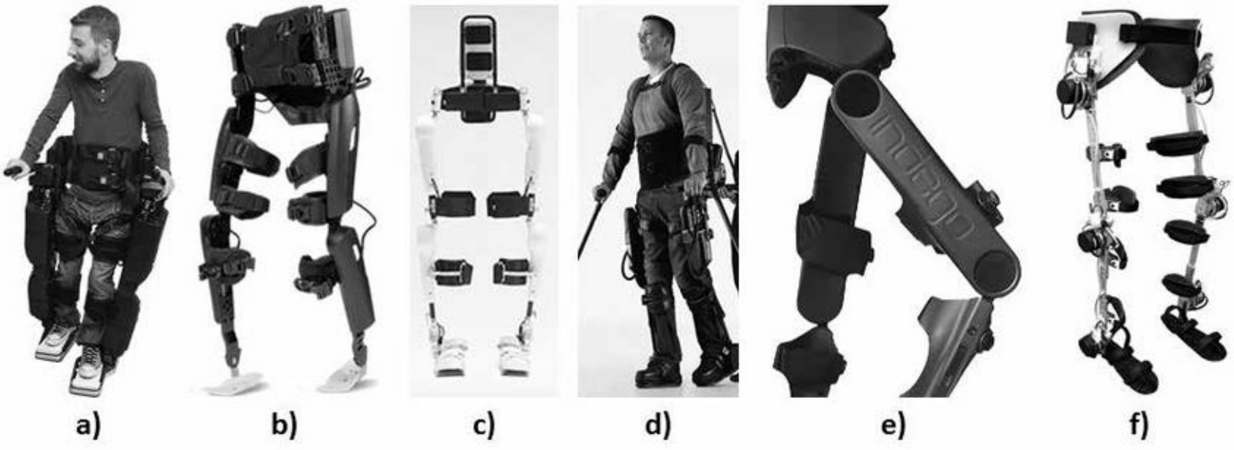


Gait Trainer GTII

Lower Limb Exoskeletons & Actuation Technology

- To address criticisms that treadmill walking does not perfectly mimic natural gait, overground robots were developed.
- ReWalk: A powered exoskeleton allowing individuals with motor-complete or incomplete SCI to walk independently overground. It uses a tilt sensor to determine the torso angle and trigger preset hip/knee displacements.
- EksoGT: A 4-DOF exoskeleton that incorporates FES (Functional Electrical Stimulation) to support muscle activation during overground walking.

Lower Limb Exoskeletons & Actuation Technology



a) Rex Bionics, b) ReWalk™, c) HAL, d) Ekso™, e) Indego®, f) H2.

Lower Limb Exoskeletons & Actuation Technology (Actuation Systems)

- For these joints to operate safely, exoskeletons rely heavily on frameless Brushless DC (BLDC) motors paired with Harmonic Drive gearing.
- Why Harmonic Drives? This specific gearing provides exceptionally high torque density and zero backlash.
- This ensures that there is no "play" in the gears, guaranteeing exact, smooth, and safe joint kinematics for the patient.

Upper Limb Therapy Robots & Impedance Control

- Upper-limb robot design is challenging due to the wide variety of symmetric, asymmetric, and unilateral activities the arm and hand perform.
- **MIT-Manus / InMotion Arm:** A planar, 2-DOF end-effector robot supporting shoulder and elbow movements in 2D space.
- The MIT-Manus utilizes impedance control to safely guide the patient's arm. Instead of rigidly forcing the arm to a location, the robot acts like a programmable spring-mass-damper system:

$$F_{robot} = M_d(\ddot{X}_d - \ddot{X}) + B_d(\dot{X}_d - \dot{X}) + K_d(X_d - X)$$

Where M_d, B_d, and K_d are the desired virtual mass, damping, and stiffness matrices, X_d is the target trajectory, and X is the actual position of the patient's hand. If the patient spasms, the "spring" (K_d) yields safely.

Upper Limb Therapy Robots & Impedance Control

Rehabilitation robots: (a) MIT-MANUS; (b) InMotion ARM ™.

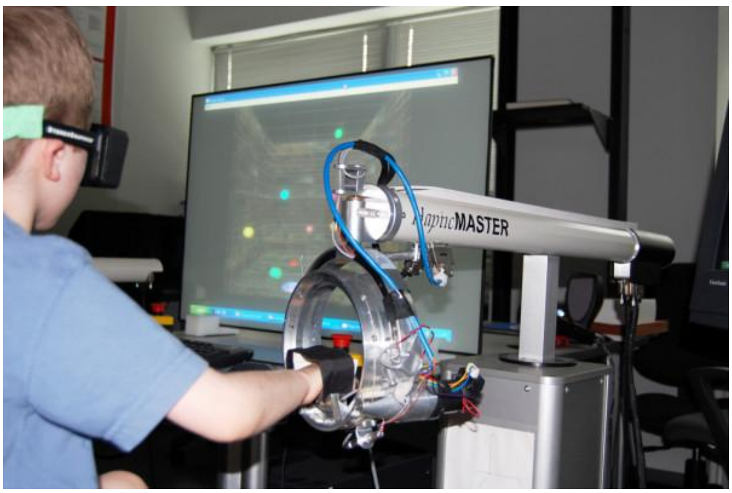
Upper Limb Therapy Robots & Admittance Control

- Because early systems showed modest improvements in ADL function, newer robots focused on reaching/grasping real or virtual objects.
- **The Haptic Master:** A 6-DOF end-effector robot that uses admittance force control to produce large forces (>100 N) with minimal friction.
- **Admittance control** is the dual of impedance control. The robot's force sensor reads the force the patient is applying (F_{user}), and the microcontroller calculates the resulting target velocity ($X^{\cdot}_{desired}$) using a virtual dynamical model:

$$\dot{X}_{desired}(s) = \frac{1}{M_d s + B_d} F_{user}(s)$$

- The inner PID loop then drives the motors to achieve this computed velocity, making the heavy robot feel weightless to a weak stroke patient.

Upper Limb Therapy Robots & Admittance Control



The subject positioned in the Leckey Chair interfaced with the Haptic Master using a ring gimbal.

Upper Limb Therapy Robots (Exoskeletal Systems)

- **ArmIn / ArmeoPower:** An exoskeletal robot providing "patient-directed" assistance (giving help only as needed). It features 7 DOF supporting the shoulder, elbow, forearm, wrist, and hand.
- **T-Wrex / ArmeoSpring:** A passive, body-powered orthosis that uses easily adjustable elastic bands to support the limb against gravity, but cannot actively move the arm via motors.
- *Armeopower vs Armeospring?*

ArmeoPower

ArmeoSpring

Wearable Upper Limb Robots & Multimodal BCIs

- A recent trend focuses on upper limb robots that can be used outside the clinic to increase therapy dosage.
- **MyoPro:** A wearable upper extremity exoskeleton that uses surface EMG to detect electrical signals from the biceps and triceps, providing proportional motor assistance.
- Bio-signal Prototyping & BCI: Engineers frequently prototype these bio-signal processing pipelines using microcontrollers like the Raspberry Pi to perform real-time filtering and integration of the EMG signal.

Wearable Upper Limb Robots & Multimodal BCIs

MyoPro

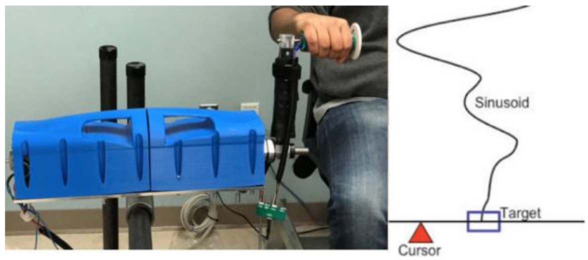
Wearable Upper Limb Robots & Multimodal BCIs

- **The Next Frontier:** Multimodal fNIRS-EEG BCIs. To assist patients with zero residual muscle movement (e.g., severe stroke or ASD executive function studies), hybrid Brain-Computer Interfaces are being developed.
- EEG provides rapid detection of electrical cortical spikes.
- fNIRS monitors hemodynamic activities (blood oxygenation) to provide high spatial resolution of brain activity.
- Fusing these modalities enables robust real-time motor intention classification, allowing paralyzed patients to trigger the robotic assist solely through cognitive intent.

Affordable and Simpler Therapy Robots

- High commercial costs ($50,000–$200,000) prohibit robots from entering home environments.
- **Bi-Manu Track:** A lower-cost system for bilateral training of wrist and forearm movements, using simple 1-DOF robots.
- **Theradrive:** A low-cost 1-DOF robot currently in prototype phase capable of outputting 40-45 Nm to support severely impaired arms in shoulder/elbow exercises.

Bi-Manu Track



Theradrive

Introduction to Assistive Robots

- **Assistive Robots** are defined as robots that serve humans by augmenting their current function, typically used after medical remediation of the impairment is completed.
- They are designed to:

1. Perform activities that the user struggles to complete independently.
2. Replace the function of a permanently paralyzed or weakened limb.
3. Monitor and act as a companion to the user.

Wheelchair-Mounted Assistive Robots

- For patients who cannot move their arms and legs independently, wheelchair-mounted robotic arms support manipulation of the environment.
- **Manus / iARM:** A 6-DOF robot manipulator with a two-fingered gripper, featuring a passive canting mechanism for secure 3-point grasping.
- **JACO Manipulator:** A lightweight (3 kg) robot with 6 DOF and a three-fingered hand, capable of reaching 1 meter in all directions and lifting 2.5 kg.

Social and Personal Care Assistive Robots

- **SAR (Socially Assistive Robots):** Personal care robots designed to do service tasks, provide companionship, and guide exercise without physical contact.
- **Paro:** A seal-like robot used to improve mental health in nursing homes that uses tactile, light, audition, temperature, and posture sensors to interact realistically.
- **Nao, Bandit & Baxter:** Humanoid robots that walk, talk, monitor tasks, and provide personalized praise, increasing patient motivation to exercise even without a human therapist present.

Clinical Considerations & Barriers

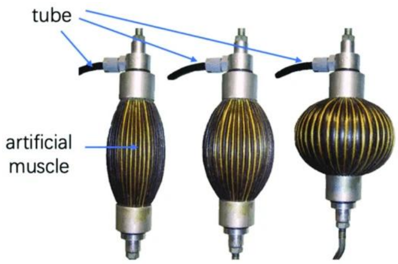
- **Advantages:** Robots provide objective, minute measurements of kinematics and kinetics and can provide high-intensity repetitive practice without fatigue.
- **Barrier 1 -** Technical Comfort: Clinicians often lack the technical expertise to set up or troubleshoot high-end technology.
- **Barrier 2 -** Setup Time: Clinicians may abandon devices if setup takes more than 10% of their allotted therapy session.
- **Barrier 3 -** Cost: High acquisition costs limit availability in community centers.

Robot Design Considerations (HAAT & Universal Design)

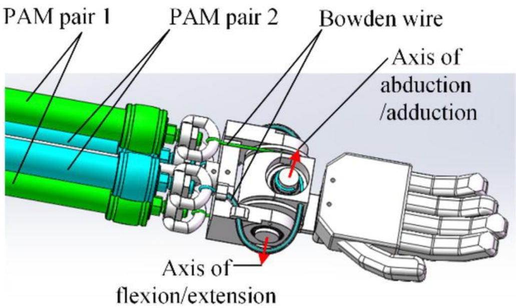
- To prevent clinical abandonment, engineers must use systematic design methodologies.
- **HAAT Model** (Human, Activity, Assistive Technology): Assesses the human stakeholders, identifies the specific activity, and evaluates the context/environment where the activity occurs.
- **Universal Design:** Products must be equitable, flexible, simple/intuitive, feature perceptible information, tolerate error, require low physical effort, and accommodate size/space variations.

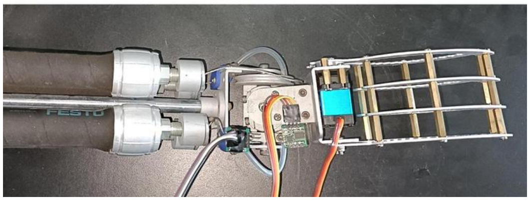
Future Directions & Soft Robotics

- **Artificial Intelligence:** Will improve the ability of robots to predict health failures or anticipate user control intent.
- **Global Access:** The engineering focus is shifting to low-cost robot systems for group-based therapy circuits to serve developing nations and low-resource environments.
- **McKibben Pneumatic Artificial Muscles:** The leading technology in safe, soft exoskeletons is the PAM. A McKibben actuator consists of a rubber bladder inside a braided sleeve.



Future Directions & Soft Robotics





The structure and the physical device of the wrist joint.

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Future Directions & Soft Robotics

- **McKibben Pneumatic Artificial Muscles:** The leading technology in safe, soft exoskeletons is the PAM. A McKibben actuator consists of a rubber bladder inside a braided sleeve.
- When pressurized, it expands radially and contracts axially, mimicking human skeletal muscle.
- The theoretical output force (F) modeled by Chou and Hannaford is driven by internal pressure (P), the initial bladder diameter (D_0), and the braid angle (θ):

$$F = P\frac{\pi D_0^2}{4}(3\cos^2\theta - 1)$$

- This equation demonstrates how force generation is highly non-linear and strictly dependent on the instantaneous geometry of the braid as the muscle contracts.

Future Directions & Soft Robotics

- Example: You are designing a soft robotic exoskeleton glove for hand rehabilitation using McKibben Pneumatic Artificial Muscles (PAMs). You need to determine how much pulling force one of these artificial muscles will generate to assist a patient in closing their fingers. Given Parameters: Operating Air Pressure (P): 300 kPa, Initial Bladder Diameter (D_0): 2 cm, Current Braid Angle (θ): 30° (during initial contraction phase). Calculate the theoretical output force (F) of the soft actuator.
- Solution: F = 117.75 N

Thank You
For Your Attention