Design criteria of rehabilitation robotic systems

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Goals of the lecture

• How to develop Human Vs Robot function allocation in the rehab arena? Why is it important?

• Taxonomies of rehab robots and of their functionality

• Why modelling the human component? How can we use it for design the rehab robot?

• What is back-driveability? Why is it important in rehab robots? How can we implement it?
Main objectives of the application of robotics to neuro-rehabilitation

• To provide the medical doctor with a ‘microscope’ for a quantitative analysis of the human sensorimotor control

• To favour an ‘industrial revolution’ in the rehabilitative scenario by means of methods and tools of bio-engineering combined with automation and robotics technologies

• To promote a ‘change of paradigm’ in the clinical protocols

Da Vinci System, Intuitive Surgical Inc.

- Master-slave manipulator equipped with 2 articulated joints at the tip of the surgical instruments allowing 7 degrees of freedom
Basic Neuroscience
(Understanding the brain)

Translational Research
connects basic research to clinical practice

Innovative Therapeutic and Assessment Technologies for NeuroRehabilitation
Basic Neuroscience
(Understanding the brain during development)

Translational Research
-connects basic research to clinical practice-

Innovative Therapeutic and Assessment Technologies for NeuroDevelopmental Engineering
General taxonomy of Rehabilitation Robots

Class I Rehabilitation Robots
- Complex mechanics
- High accuracy and precision
- Expensive and quite bulky

Class II Rehabilitation Robots
- Simpler mechanics
- Low\medium accuracy and precision
- Lightweight, portable systems
- Low cost

MEMOS (2002)
MEchatronic system for MOtor recovery after Stroke

- 8 patients (mean age 55.4 years old, range 33–67 years old)
- Chronic hemiparesis (mean months after the event 20)
Design approach to next generation rehabilitation robots

KEY ISSUES

• Top-down
• Human-centred
• Biomechatronic
Biomechatronic design approach
Human Component Modeling

- Simulation and evaluation of the dynamics of the human-robot coupled system
- Simulation, modeling and evaluation of sensorimotor pathologies and disfunctions of biological systems
- Optimizing the machine design
Design approach to next generation rehabilitation robots

Adapted from: Assistive Technologies Principles and Practice, AM Cook, SM Hussey, Mosby Inc. 2002
Design approach to next generation rehabilitation robots

Adapted from Assistive Technologies Principles and Practice, AM Cook, SM Hussey, Mosby Inc. 2002
Design approach to next generation rehabilitation robots

- Analysis of person-activity interface
- Optimal allocation of roles

Adapted from: Assistive Technologies Principles and Practice, AM Cook, SM Hussey, Mosby Inc. 2002
Optimal allocation of roles
The Decision Space
(Price et al., 1982)

Excellent

Machine Performance

 Unsatisfactory

Human Performance

Excellent

Unsatisfactory

Excellent

Unsatisfactory

Excellent

Human Performance

Excellent

Unsatisfactory
Top-down biomechatronic design approach

- Analysis of person-activity interface
- Optimal allocation of roles
- Interaction design
- Functional requirements
Basic functional requirements
(1 of 2)

• **Physical Interaction**
  – Constrained motion
  – Minimum perturbation of natural motion
  – Type and level of pathology addressed

• **Functional Interaction = Human Centred - triadic**
  – Active patient role (also for severe disabilities)
    • Human trigger
    • Predefined time-threshold
    • Adaptive level of assistance during motion
  – Optimization of the role of the therapyst (max effectiveness)
Basic functional requirements (2 of 2)

- Limb (or part of) addressed
- Interface metaphor (games, ADL, ecc.)
- Type of motor exercises:
  - ROM of target human joints
  - Applied force ranges
  - Kinematic and/or dynamic constraints
- Exteroceptive inputs
  - Patient sensory data
  - Environmental sensory data
General taxonomy of operation modes of rehabilitation robots

(Guglielmelli et al., in Neurorobotica, Dario et al. (eds), 2006)

<table>
<thead>
<tr>
<th>BASIC OPERATION MODE</th>
<th>ROLE OF THE ROBOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Passive</td>
<td>Pre-programmed motor tasks, minimal active interaction with the patient</td>
</tr>
<tr>
<td>2. Master-Slave</td>
<td>Tele-operated by the therapist</td>
</tr>
<tr>
<td>3. Constrained</td>
<td>Volitive action of the patient on a predefined virtual trajectory generated by the robot</td>
</tr>
<tr>
<td>4. Assisted</td>
<td>Generation of force fields to augment or contrast human motion, enhanced interaction with the patient</td>
</tr>
<tr>
<td>5. Bilateral</td>
<td>Bimanual tasks (combined with any of the other modes above). In emileptic patients, it often refers to tele-operated mode when using as master input the movement of the unimpaired limb.</td>
</tr>
<tr>
<td>6. Assessment</td>
<td>Minimal possible perturbation of natural motion while mechanically copying it</td>
</tr>
</tbody>
</table>
Top-down biomechatronic design approach

- Analysis of person-activity interface
- Optimal allocation of roles
- Interaction design
- Functional requirements
- Human component model
- Mechatronic Machine Design
- Design Optimization by analyzing\simulating\testing performance of the integrated human-robot system

( Guglielmelli et al., in Neurorobotica, Eds. P. Dario et al., 2006)
Top-down biomechatronic design approach

- Human component model
- Control sub-system design
- Mechanical design
- Mechatronic optimization process
OPERATIONAL Rehabilitation Robots

– In the OPERATIONAL space, the trajectories of the robot end-effector and of the human end-effector (wrist\hand or ankle\foot) are COUPLED

– In the JOINT space, the trajectories of the robot joints and of the human joints are INDIPENDENT
– The patient is expected to exploit her/his own synergies at joint level to follow a trajectory in the operational space
– Mainly appropriate for patients with moderate disabilities, i.e. patients that feature a sufficient level of residual motor synergies
Exoskeleton-like rehabilitation robots

- In the OPERATIONAL space, the trajectories of the robot end-effector and of the human end-effector (wrist\hand or ankle\foot) are the same
- In the JOINT space, the trajectories of the robot joints APPROXIMATE those of the human joints
Exoskeleton-like rehabilitation robots

- Wearable (bio)-mechatronic systems, i.e. the human-machine interface is extended all along the limb (or its portion of interest)
- The number of DOFs is at least the same as that of the joints on which the therapy is expected to have an effect
- The motor exercise can be directly defined in the joint space
- Useful for severely disabled persons whose natural synergies have been altered and need for a separate control of the different joints in order to restore the natural motor control strategies
Top-down biomechatronic design approach

- Human component
- Model
- Control sub-system design
- Mechanical design
- Mechatronic optimization process
Functiona block scheme of robot control

Control In the Joint Space
(applicable to operational and exoskeletal machines)

Control In the Operational Space
(applicable to operational machines)
Control of physical human-robot interaction

Interaction Control

Unstructured environment

Structured environment

Impedance Control

Compliance Control

Force Control

Hybrid Force/Position Control

with inner position loop

with inner velocity loop

parallel force/position


[Zollo, Dipietro, Siciliano, Guglielmelli, Dario. J. Rob. Syst., 2005]
Bio-inspired control schemes

Coactivation-based compliance control in the joint space


Modelling human-robot physical interaction
Human arm model

- 2-dof planar model
- Model dofs: shoulder angle ($\theta_1$) and elbow angle ($\theta_2$)
- 2 rigid links: arm ($l_1$) and forearm ($l_2$)

$$B_{HUM}(\theta)\ddot{\theta} + C_{HUM}(\theta, \dot{\theta})\dot{\theta} = \tau_{HUM} - J_{HUM}^T(\theta)F_{HUM}$$

Human motor control modeled with a visco-elastic behavior, described as:

$$\tau_{HUM} = R_{HUM}(\theta_d - \theta) - D_{HUM}\dot{\theta}$$

Human arm dynamics and kinematics (Katayama & Kawato, Adv. Rob., 1991)
Planar SCARA manipulator: 4 links, 2 independent dofs:

\[ B_{\text{ROB}}(q) \ddot{q} + C_{\text{ROB}}(q, \dot{q}) \dot{q} = \tau - J_{\text{ROB}}^T(q)F_{\text{ROB}} \]
Human-robot integrated model

Constrained motion is used to derive an integrated human-robot model:

- Same position, velocity and acceleration in the operational space at the end-effector
- Equal and opposite interaction force at the end-effector

\[
\begin{align*}
\theta &= k_{HUM}^{-1}[k_{ROB}(q)] \\
\dot{\theta} &= J_{HUM}^{-1}(\theta)[J_{ROB}(q)\dot{q} + J_{ROB}(q)\ddot{q} - J_{HUM}(\theta)\dot{\theta}] \\
F_{HUM} &= -F_{ROB}
\end{align*}
\]

SIMULINK implementation
Simulation tool

Graphical interface:
- Human arm (pink)
- MIT-MANUS robot (black)
- Handle of the robot (yellow)
Simulation tool

Graphical interface:
- Human arm (pink)
- MIT-MANUS robot (black)
- Handle of the robot (yellow)

Simulation of able-bodied subject
Simulation tool

Simulation of three different pathological behaviour:

Healthy subject

Slight disability

Medium disability

Severe disability
Simulation tool

Graphical interface:
- Human arm (pink)
- MIT-MANUS robot (black)
- Handle of the robot (yellow)

Simulation of impaired patient
Using data from real patient sessions for simulations

Simulation of robot-aided motor therapy with a post-stroke patient
COMPARATIVE EVALUATION OF DIFFERENT INTERACTION CONTROLS FOR ROBOT-AIDED NEUROREHABILITATION

Standard interaction controls:

- COMPLIANCE CONTROL
  - in the Cartesian space
  - in the joint space

VS

Bio-inspired interaction controls:

- SELF-REGULATED COMPLIANCE CONTROL
- COACTIVATION-BASED COMPLIANCE CONTROL
- TORQUE-DEPENDENT COMPLIANCE CONTROL

IN 4 DIFFERENT OPERATING MODALITIES

1. Point-to-point movement in the free space
2. Point-to-point movement in an unstructured environment (collision with an obstacle)
3. Point-to-point movement in the constrained space (interaction force in the whole movement)
4. Point-to-point movement with external disturbance (patient pathology simulation)
5. Point-to-point movement with a patient
Top-down biomechatronic design approach

- Human component Model
- Control sub-system design
- Mechanical design

Mechatronic optimization process
Design criteria

- The machine is required to have a high transparency, i.e. the ability of being moved by the patient with negligible perturbation of natural motions.

back-driveability
Back-driveability: mechanical considerations

- Back-driveability is the ability of robots of being moved by applying forces to their end-effector, instead of forces/torques to their joints, as it happens in direct motion.

- High back-driveability means:
  - Kinematic invertibility, i.e. high kinematic efficiency during the reverse motion.
  - Low perceived inertia during the reverse motion.
Kinematic invertibility

**Direct motion:** *the car climbs up the slope* – performing work against gravity –

**Reverse motion:** *gravity pushes the car downhill.* This is possible IFF car internal friction is low enough (e.g. no gear inserted)

A mechanism is kinematically invertible if reverse motion is possible (i.e. friction is low enough: kinematic efficiency > 0.5)
Back-driveability: kinematic invertibility

Let $L_r$ be the work of resistive forces and $L_m$ the work of motor forces.

The efficiency of a kinematic structure is: \[ \eta = \frac{L_r}{L_m} \]

When the same structure is working in reverse mode, its kinematic efficiency is given by:

\[ \eta' = \frac{L'_r}{L'_m} = \frac{L'_r}{L_r} \]
Back-driveability: kinematic invertibility

Through simple calculations one can find:

\[ \eta' = \frac{\eta(1+k) - k}{\eta} \quad \text{where} \quad k = \frac{L'}{L} \approx 1 \]

Reverse motion is possible if:

\[ \eta' > 0 \iff \eta > \frac{k}{1+k} \approx 0.5 \]

In conclusion, a kinematic structure can operate in reverse mode if it has a high kinematic efficiency (> 0.5).
Back-driveability: kinematic invertibility

The kinematic structure of a robot is obtained by properly linking a number of kinematic couples.

\[
\eta = \prod_{i=1}^{N} \eta_i \quad (\eta \leq \min\{\eta_i\})
\]

The efficiency of a series transmission quickly drops to zero for increasing \( N \).

\[
\eta = \frac{1}{L} \sum_{i=1}^{N} L_i \eta_i \quad (L = \sum_{i=1}^{N} L_i)
\]

The efficiency of a parallel transmission depends on the motor work through each kinematic couple.
Back-driveability

Kinematic invertibility is a necessary but not sufficient condition for having back-driveability. Also mass (inertia) matters!

A bicycle is back-driveable (have you ever tried to walk your car?)

When a machine is not intrinsically (i.e. mechanically) back-driveable, mechatronics can help. Let's see these concepts applied to rehabilitation robots.
• During reverse motion, the dynamic properties of the structure can change dramatically.

• It is therefore necessary to verify that the *apparent inertia*, i.e. the inertia perceived at the end-effector during back-driven motion, is sufficiently low not to significantly perturb the natural motion of the limb.
Back-driveability
(purely mechanical)

Direct motion: energy flows from the actuators to the human limb

Reverse motion: energy flows from the human limb to the actuators
Back-driveability (mechatronic)

Direct and reverse motion: energy flows from the actuators to the human limb

Reverse motion: the intention of motion of the patient is transduced to the actuators, which perform work to win friction and inertia
General Design Criteria

A mechanically back driveable robot requires:

- Low inertia (both in direct and reverse motion)
- Kinematic invertibility

Additional features that can help controlling the system:

- Rigid mechanical structure
- Negligible or small non lineairities (no backlash, low coulombian friction)
Design criteria: transmissions

• Trasmissions change the properties of a motion (application point and direction of forces/torques; power factors: force/velocity or torque/angular speed).

• The most common solutions include:
  • Rigid members (screws, gears)
  • Flexible members (cables and belts)
Screws convert a rotational motion into a linear motion, and vice-versa (in the reverse motion).
Design criteria: rigid transmission

\[ \eta = \frac{\cos \alpha_n - f \tan \lambda}{\cos \alpha_n + f \cot \lambda} \]

- \( f \) = friction coefficient
- \( \alpha_n \) = inclination angle of screw thread on the plane orthogonal to the tooth
- \( \lambda \) = helix angle

**Square thread** (\( \cos \alpha_n = 1 \))

Kinematic reversibility (\( \eta > 0.5 \)) cannot be achieved for all geometries and only when friction coefficient is sufficiently low.
Design criteria: rigid transmission

Gears modulate the power product: \( \text{torque} / \text{angular velocity} \) according to the desired task.

The efficiency quickly decreases with the number of gears.
Design criteria: flexible transmission

The most used flexible elements are: belts (smooth or toothed), chains and cables.

The same kinematic couples which can be obtained using rigid members can be obtained using flexible members.

A cable in capstan (sin) configuration is kinematically equivalent to rack and pinion (dx)
MACARM: Multi-Axis Cartesian-based Arm Rehabilitation Machine

System with 6 DoF obtained through 8 active modules mounted at the vertexes of a box frame

Each module is comprised of: 1 DC brushless motor, 1 encoder, 1 harmonic drive reduction gear, a pulley

The number of active modules depends on the specific motor task

Design criteria: flexible transmissions

Example: linear module using a timing (i.e. toothed) belt. The stiffness is guaranteed by the linear support on which purposively shaped cylinders roll. Such cylinders sustain torques/forces so that pure tensile stresses are exerted on the belt.

Pros

• Light weight
• Low cost
• Low friction

Cons

• Elasticity
• Irreversibility (depending on the configuration, just tensile, not compressive, forces can be transmitted, so that an agonistic/antagonistic configuration required)
Design criteria: transmissions

- Transmissions heavily impact not only the kinematic efficiency but also apparent inertia during back-driven motion.

- **Rule of thumb**: transmission ratios much higher or much smaller than one produce high apparent inertia.

- For this reason, reduction gears are often avoided, by directly coupling the actuators to the structure (**direct-drive configuration**)
Most commonly used actuators in neurorehabilitation machines are:

- **DC motors**: largely the most widely used thanks to their high controllability.
- **Stepper motor**: low cost, they show a torque ripple which is sometimes not acceptable.
- **Pneumatic actuators**: they can be either rotary or linear. High power density. They require a compressor and are often irreversible.
Design criteria: actuators

- **McKibben muscle** comprises:
  - A tube-shaped elastic chamber, which expands radially when inflated;
  - An external system of inextensible helices, having 1 DOF: its radial deformation causes an axial contraction.

- **It shortens when inflated:** can be used in agonistic/antagonistic configuration

**Characteristics**
- Pressure: ($<$) 5 bar
- Strain: ($<$) 60%
- Dimensions: from few cm to several tens of cm.
- Controllability (low friction)
- Light weight
- Intrinsic elasticity
LOWER BODY EXOSKELETON

Mechanical structure with 10 DOF

- Hip joint (3 dof):
  - flexo-extension
  - abduction/adduction
  - Lateral rotation: not implemented

- Knee: (1 dof): flexo-extension

- Ankle (1 dof): dorsal and plantar flexion

LOWER BODY EXOSKELETON

- Pneumatic actuation (McKibben muscles, 2 cm diameter; length at rest: 50-70 cm)
- Total weight (bilateral, 2 limbs): 12 kg

<table>
<thead>
<tr>
<th>JOINT / SEGMENT MOVEMENT</th>
<th>Human Isometric Strength/Range</th>
<th>Achieved Joint Torque Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion/Extension</td>
<td>110Nm 120°/20°</td>
<td>60Nm 135°/45°</td>
</tr>
<tr>
<td>Adduction/abduction</td>
<td>125Nm 45°/30°</td>
<td>65Nm 135°/135°</td>
</tr>
<tr>
<td>Internal Rotation</td>
<td>35°-45°</td>
<td>110°</td>
</tr>
<tr>
<td>External Rotation</td>
<td>45°-50°</td>
<td>110°</td>
</tr>
<tr>
<td>KNEE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion/Extension</td>
<td>72.5Nm 140°</td>
<td>60Nm 140°</td>
</tr>
<tr>
<td>ANKLE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plantar Flexion/Dorsiflect</td>
<td>19.8Nm 50°/30°</td>
<td>60Nm 105°/45°</td>
</tr>
</tbody>
</table>
Design criteria: actuators

It is possible to fabricate actuators with variable impedance by using electrically controlled brakes.

Example: DC motor directly linked to a brake using an electrorheological (ER) fluid. The viscosity of the liquid greatly changes when immersed in an electric field.
CBM-Motus Case study

- We are currently developing a mechanically back-driveable 2-dof planar robot, the CBM-Motus, with some additional features:
  
  - Isotropic inertia (i.e. not depending on the direction of motion)
  - Homogeneous inertia (i.e. not depending on the end-effector position)
  - Therefore: A (very) simple dynamics
CBM-Motus Case study

- Standard solution 1: XY stage with screw-lead drives where one stage (distal) is drawn into motion by the proximal one

Screws are usually not invertible (do not counter-rotate if pulled): this choice would require mechatronic back-driveability
CBM-Motus Case study

- Standard solution 2: XY stage with belt transmission where one stage (distal) is drawn into motion by the proximal one

This solution is kinematically invertible. But during user-driven motion, the inertia perceived along the axis of the proximal stage is much higher than that perceived along the axis of the distal stage.
Design hint: decoupling degrees of freedom is desirable for achieving a good back-driveability:

“The PHANTOM has been designed so that the transformation matrix between motor rotations and endpoint translations is nearly diagonal. Decoupling the three motors produces desirable results in terms of back-drive friction and inertia.”

A completely decoupled 2-dof planar robot has a diagonal Jacobian matrix ($J$) and a diagonal inertial matrix in the joint space ($B$). From a mechanical point of view, this can be achieved by building the robot with two decoupled modules orthogonally assembled. In particular, if the two modules are identical, then

$$J = \begin{pmatrix} j(q_1) & 0 \\ 0 & j(q_2) \end{pmatrix}, \quad J_{ij} := \frac{\partial x_i}{\partial q_j}$$

$$B = \begin{pmatrix} b(q_1) & 0 \\ 0 & b(q_2) \end{pmatrix}, \quad B_{ij} := \frac{\partial \tau_i}{\partial \ddot{q}_j}$$

A last simplification can be achieved if kinematic and inertial characteristics are configuration independent.

**Such a structure has an isotropic and homogeneous inertia:**

$$\Lambda = J^{-T} B J^{-1}$$

$$\Lambda = \lambda \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$
CBM-Motus: design

Each module comprises 6 pulleys, two of which are mounted on the same shaft (C and D), and 2 timing belts.

One pulley is driven by a fixed motor.

The two belts are mounted in such a way that the points along the segments $AB$ and $CD$ move vertically with the same speed.

A bar is connected to a couple of such points. E.g. The bar between $P$ and $P'$ allows the motion along the $y$ direction.
CBM-Motus: design

Two modules are mounted with a 90° rotation. The resulting kinematic structure is depicted in the schematic below.

The end effector (E) is connected to the sliding bars via a double prismatic joint (A and B).

The prismatic joints (P1...P4) are actuated by the belts.
CBM-Motus: design


The double prismatic joint decomposes the forces applied to the end-effector in such a way that each belt is *stretched* but not *bent*: although the transmission is flexible, the structure is rigid. Moreover, vertical loads are supported by the frame via a rolling ball bearing support.
CBM-Motus: specifications

Workspace: 500 mm x 500 mm
Inertia (*): 2.6 kg (isotropic and homogeneous)
Max speed: 400 mm/s
Max force: 50N (0.5 mm max def @ 100N)

Motors: 2 DC brushless (BM-150 Aerotech), no reduction gear (2 Nm nominal torque, 4 Nm peak torque)

Overall size: 850 mm x 850 mm x 100 mm
Weight: 20 kg (motors included)

(*) Including load cell and handle.
Design optimization

- CBM-Motus dynamic properties have been studied in terms of robot inertia and acceleration characteristics as perceived at the end effector.

\[ \Lambda(q) \dot{\theta} + \mu(q, \dot{q}) + p(q) = F \]

Fabrication


The CBM-Motus will be an experimental platform with low isotropic and homogeneous inertia for a safe interaction with the patient during the robot-aided motor therapy.

The simple and configuration independent dynamic model makes inverse dynamics controls easy to be implemented with a very low computational cost.

The robot can also be used for measuring human arm performances without perturbing the natural motion.

Application to tele-rehabilitation and home rehabilitation is foreseen.
UCBM BIOMEDICAL ROBOTICS AND BIOMICROSYSTEMS LAB

Permanent staff

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Assistant Professor of Biomedical Robotics

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Post-doc Research Fellow
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Emilio Gallotta, Physical Therapist, Research Assistant

Average Age < 26 yo
Integrated Research Centre in Biomedicine and Bioengineering