BIOMECHANICS:
Lecture #7 – Robot Mediated Therapy

Facoltà di Ingegneria
Civile e Industriale

Sapienza
Università di Roma

1. Introduction
2. Rehabilitation robotic systems
3. Effectiveness
4. Robot mediated therapy at @SAPIENZA

1. Introduction on robot mediated therapy

2. Rehabilitation robotic systems
3. Effectiveness
4. Robot mediated therapy @SAPIENZA

Introduction: Mechanics

automaton

μηχανη → αυτοματα → *robotnik*

Introduction: Mechanics

ORIGINS OF THE WORD «MECHANICS»

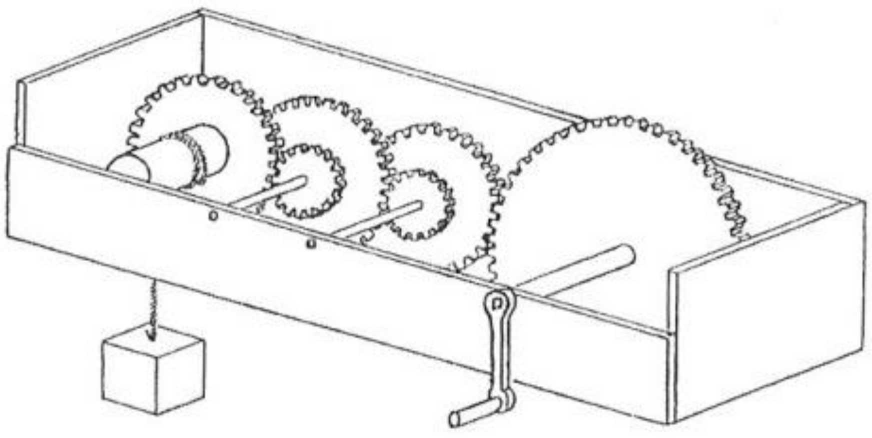
μηχανη: indicates the result of an action (verb: μηχαναω) that is surprising.

- **Positive meaning**: ability to overcome otherwise insurmountable situations;
- **Negative meaning**: to cheat by means of manoeuvring.

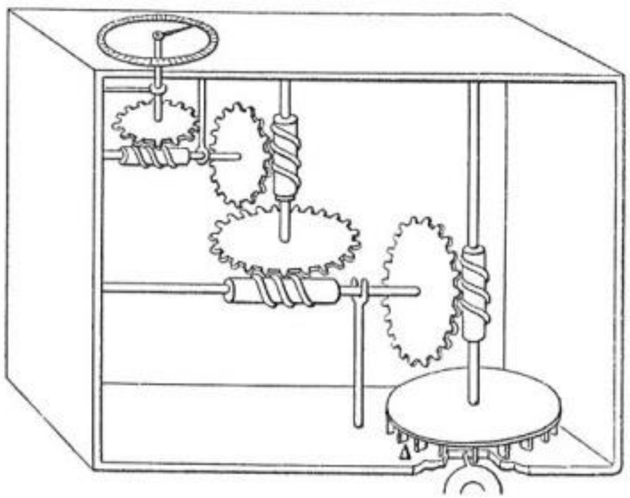
Introduction: Automata

THE GREEK WORLD

Heron of Alexandria (1st century AD):
"*Mechanica*", preserved only in Arabic, containing means to lift heavy objects.
"On the Dioptra", a collection of methods to measure lengths.



Schematic diagram of the **baroulkos**, a mechanism used for the elevation or the drawing of large load with the application of only minimal manpower

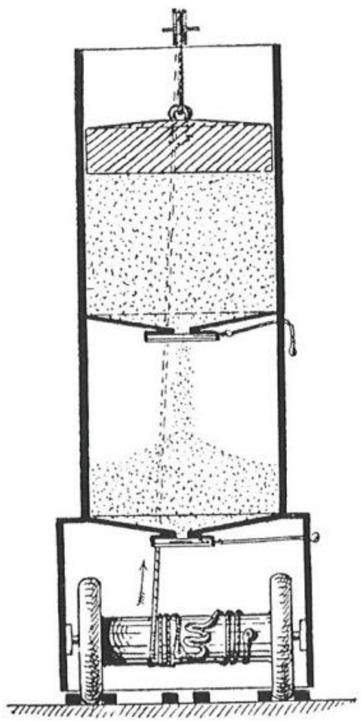


Schematic diagram of the **odometer**, an instrument that measures distances traveled

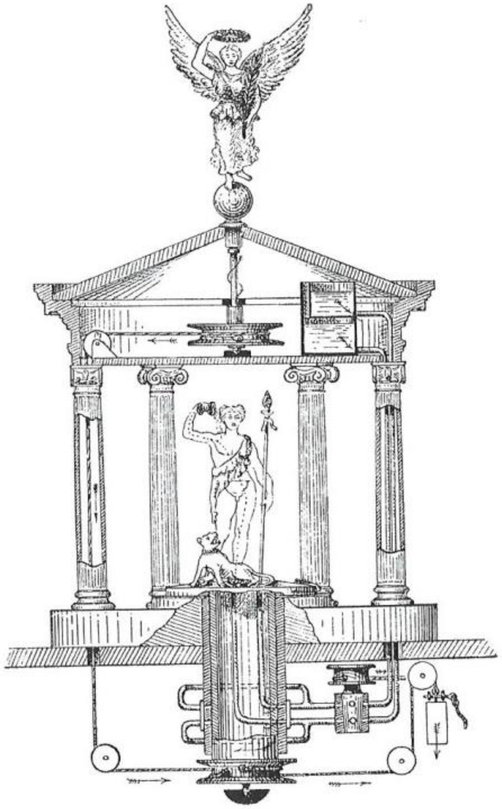
Introduction: Automata

THE GREEK WORLD

Heron of Alexandria (1st century AD):
Automata, a description of machines which enable wonders in temples by mechanical or pneumatical means.



Schematic diagram of an engine for Heron's theatre



The theatre described by Heron in "Automata", the only ancient automatic mechanism known in detail

Introduction: Automata

THE ARABIC WORLD

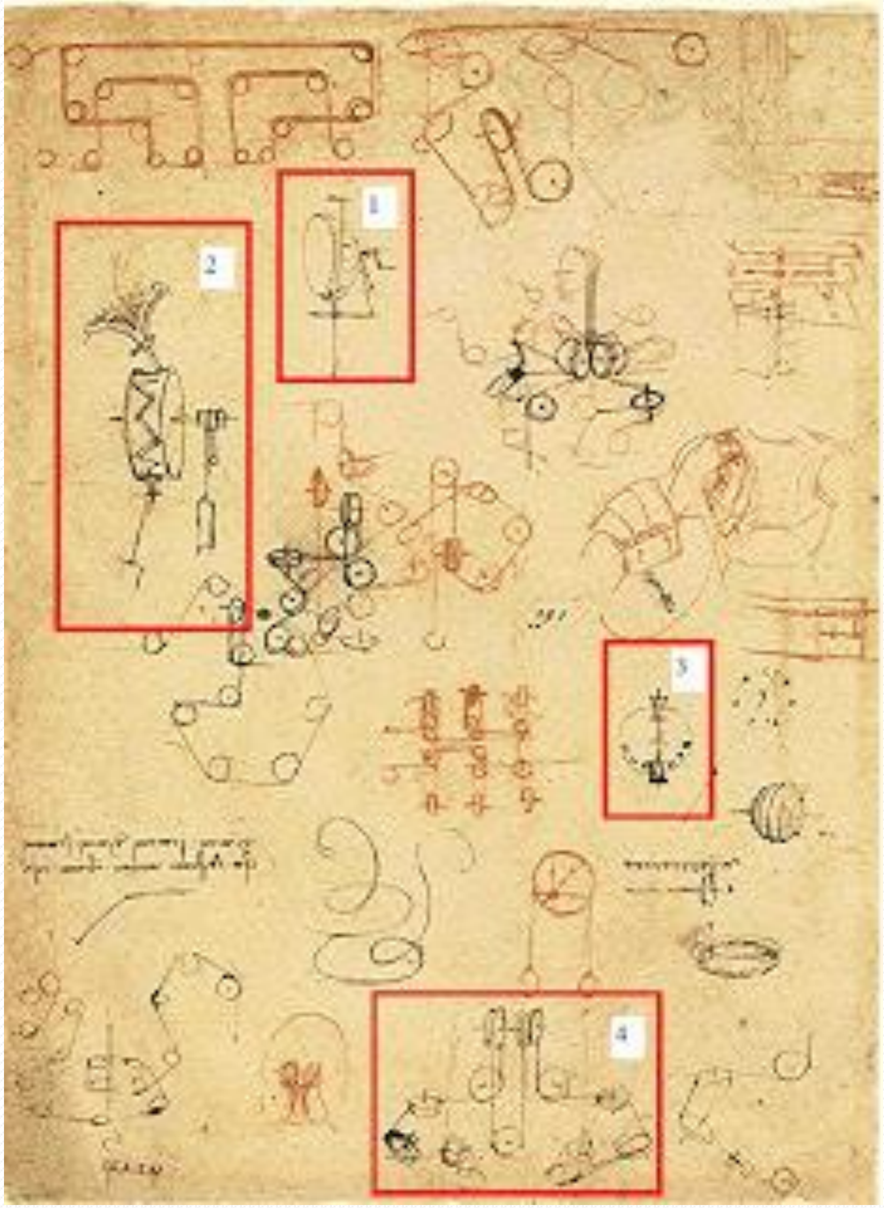
Al-Jazari (12th century AC) «The Book of Knowledge of Ingenious Mechanical Devices», the most important scientific work about Mechanics before Renaissance. Detailed decription in order to replicate the proposed mechanism:

- water clocks;
- automata (musical robot band, drink-serving waiters, etc.)

THE RENAISSANCE

Leonardo da Vinci «Codex Atlanticus folio 579r» mechanical details of a drummer robot:

1. Drum with controller
2. Programmable mechanism with reciprocating motion
3. Lantern gear with reciprocating motion
4. Pulley schematics for the motion of lower limbs



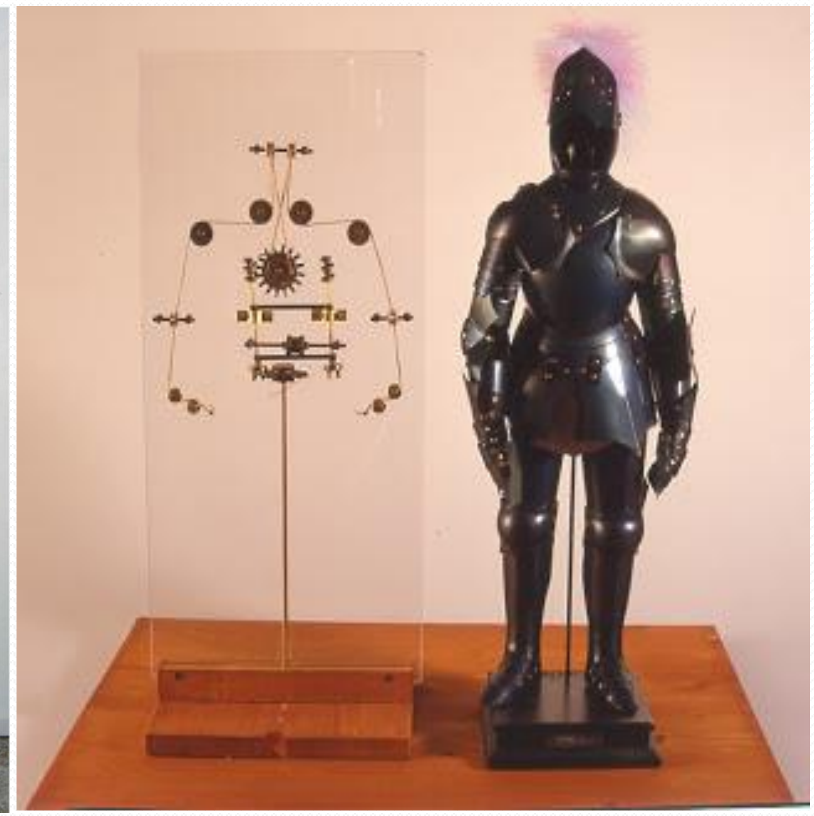
Introduction: Automata

THE RENAISSANCE

Reconstruction of the model

- Difficulties in moving the arm after few movements (5 or 6),
- Mechanical components and cables need a constant regulation.



Introduction: Automata

AGE OF ENLIGHTENMENT: *LA PHISIQUE AMUSANT*

Maillard (French mechanic): in 1733 presented some automata to the Academie Royale des Sciences:

- a swimming swan;
- two horses, the first dragging a coach, the second dragging a gondola.

Jacques de Vaucanson in 1738 presented at an exposition in Paris:

- The flute player;
- The fife and tambour player;
- The digesting duck.

The Exposition lasted a year in Paris, then Vaucanson brought his automata around France and Europe.

Introduction: Automata

AGE OF ENLIGHTENMENT: *LA PHISIQUE AMUSANT*

Jacques de Vaucanson: the flute player, 1.8 m height, could play 12 different songs, moving in a coordinate way:

- Three bellows;
- The lips;
- The fingers.

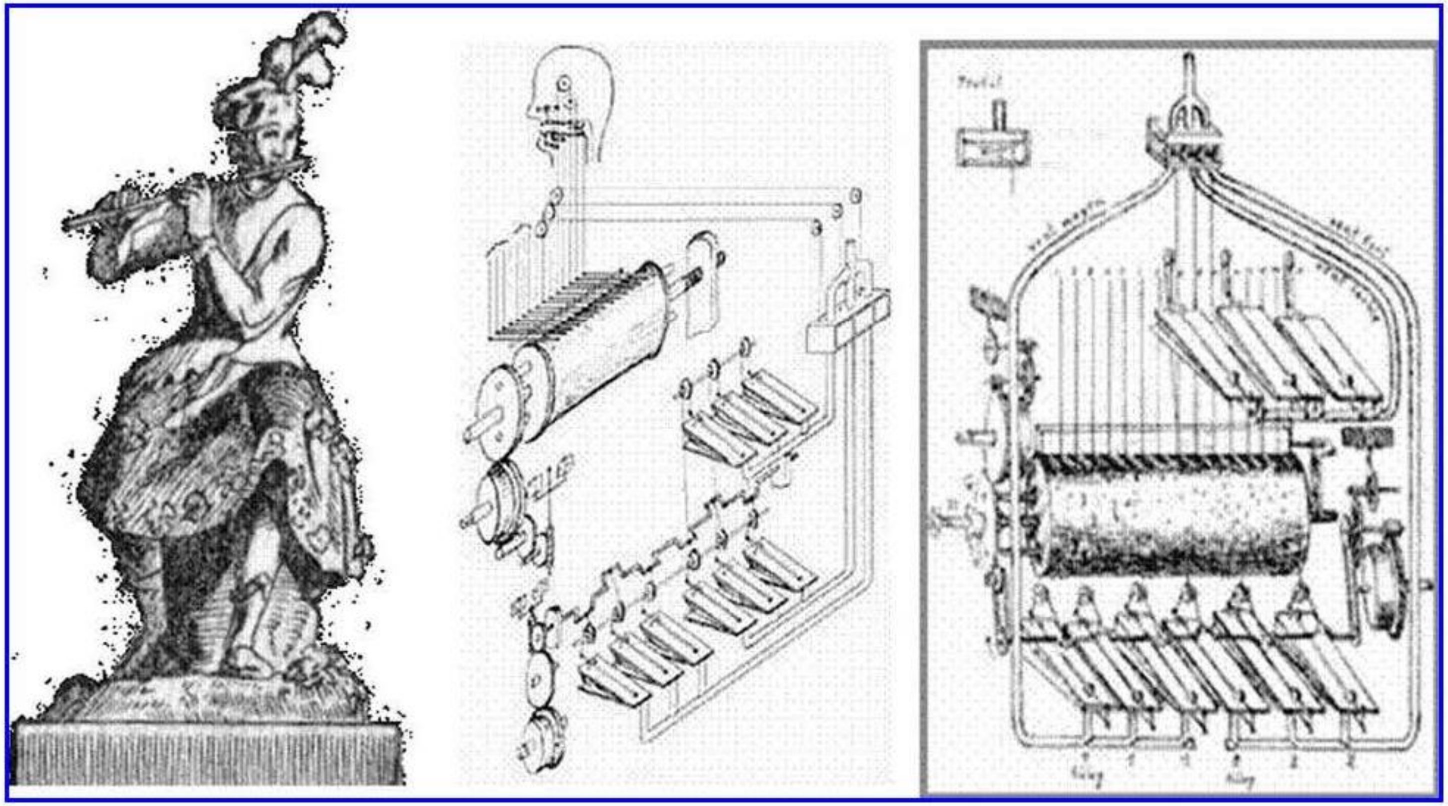


FIG. 2. The "Flutist" by Jacques de Vaucanson, circa 1737.

Introduction: Automata

AGE OF ENLIGHTENMENT: *LA PHISIQUE AMUSANT*

Jacques de Vaucanson: the digesting duck had more than 1000 moving parts (the wing only consisted of 400 elements) and a working gastrointestinal system.

The duck could:

- bend the neck,
- swallow water and flour,
- flutter and,
- defecate.

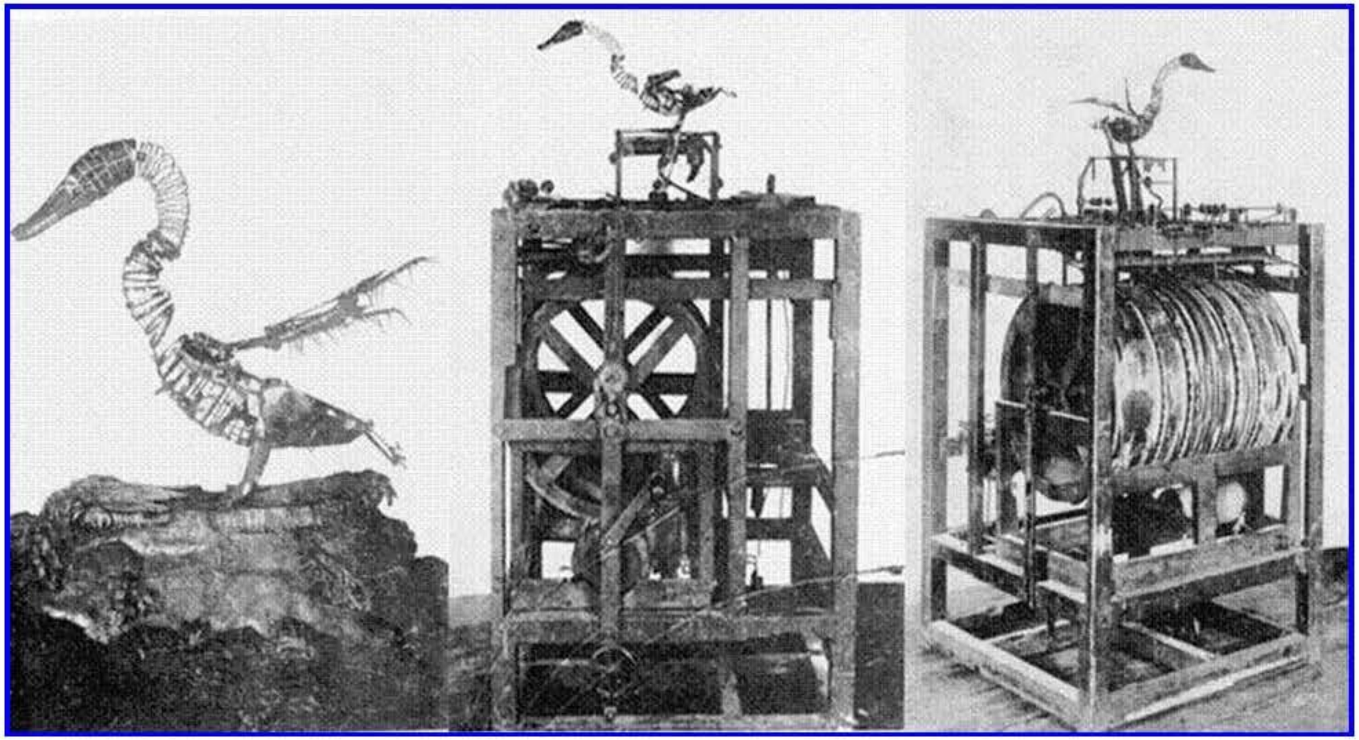


FIG. 3. Vaucanson's duck, circa 1739.

Introduction: Automata

AGE OF ENLIGHTENMENT: *LA PHISIQUE AMUSANT*

Jacques de Vaucanson: the “Fife and Tambour Player” could play 20 songs

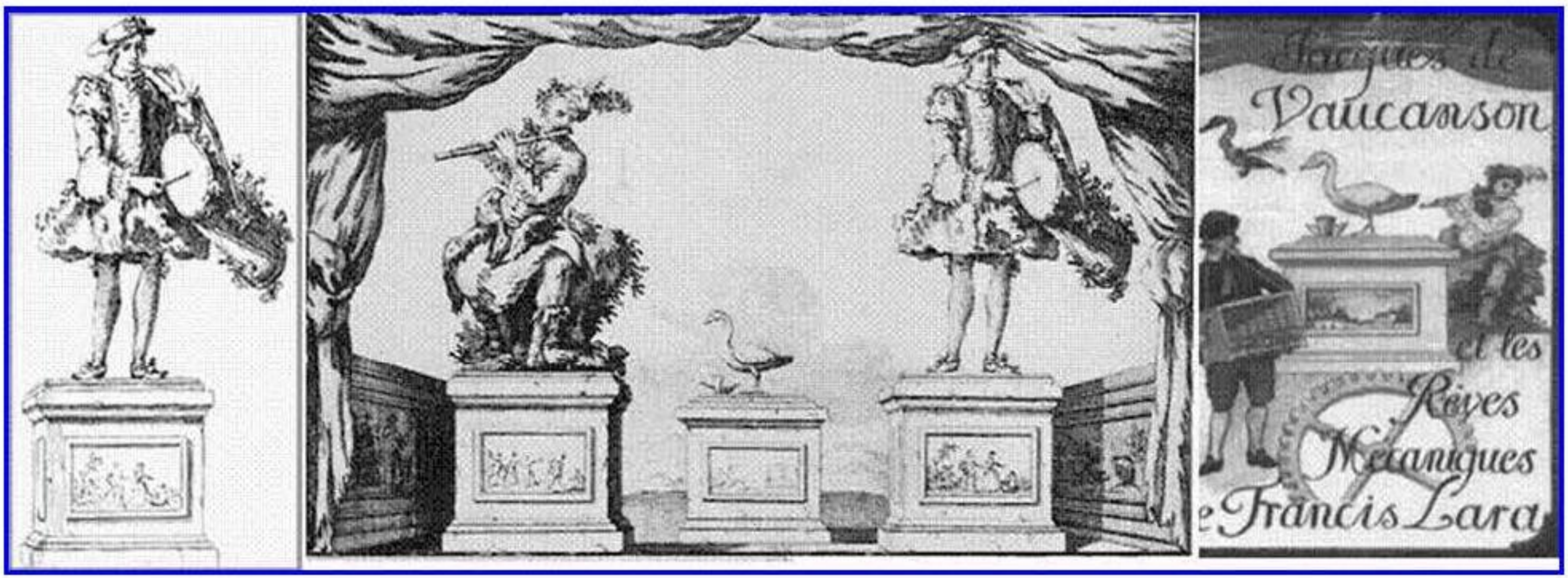


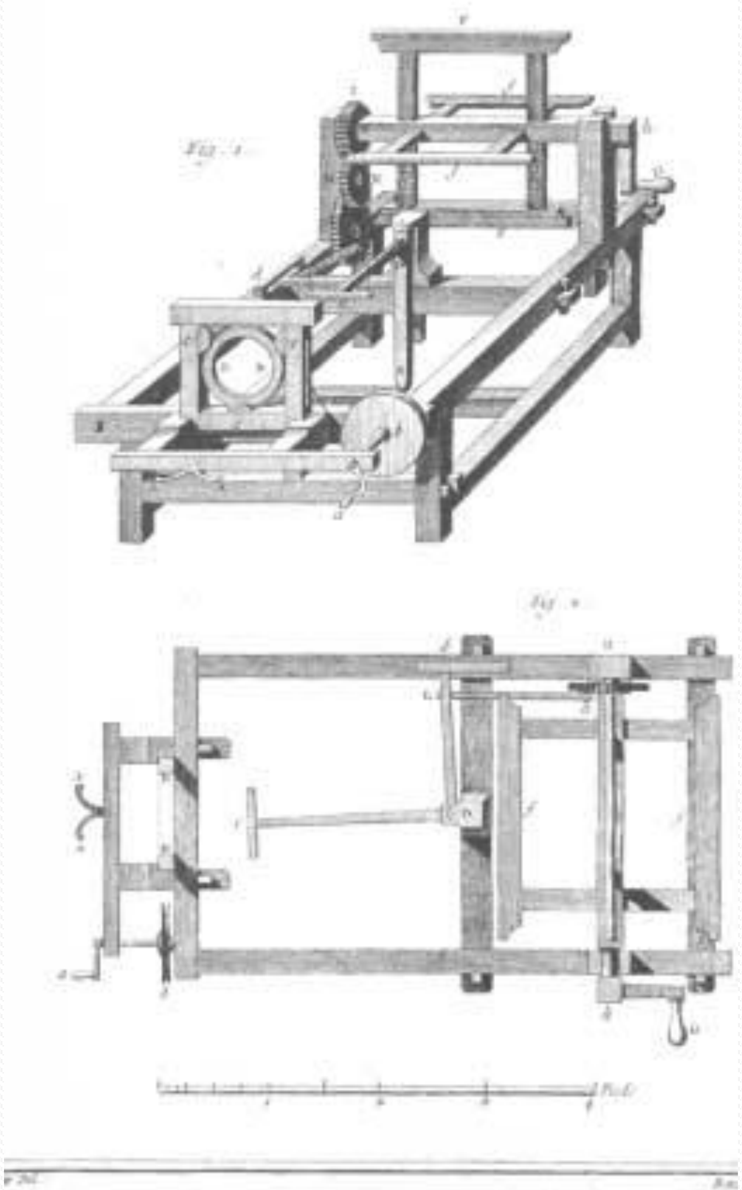
FIG. 4. The “Fife and Tambour Player,” circa 1739.

Introduction: Automata

AGE OF ENLIGHTENMENT: *LA PHISIQUE AMUSANT*

Jacques de Vaucanson:

- Simulator in medical field (Académie de Lyon, 1741) that simulated by means of a musculoskeletal system the movement of fluids:
    - blood circulation;
    - breathing,
    - digestion.
- Industrial application: mechanical loom.



Soierie, Tour de M.r de Vaucanson

Introduction: Automata

ORIGINS OF THE WORD «ROBOT»

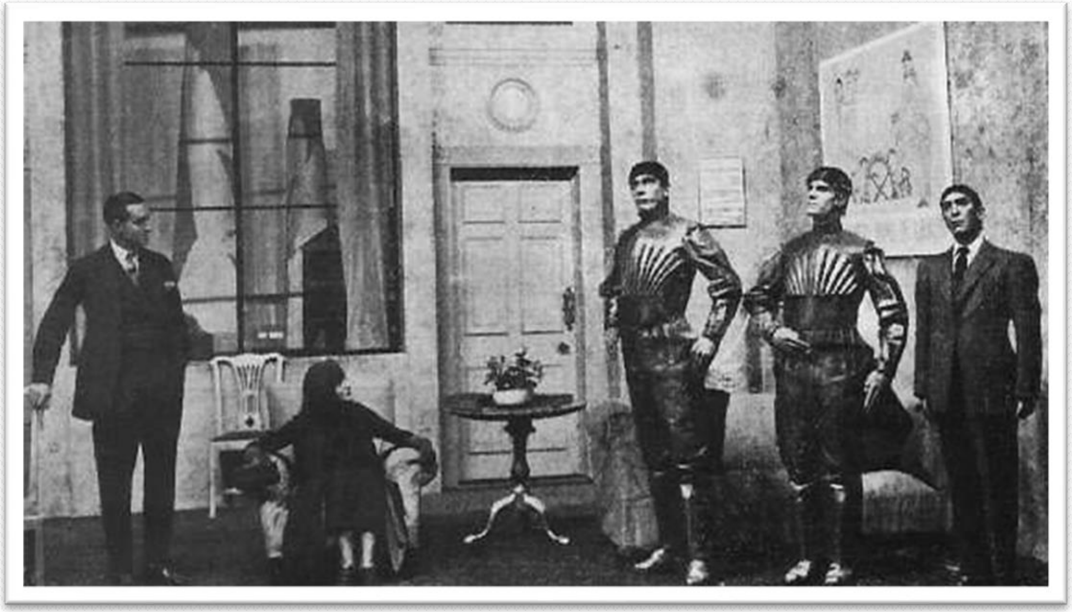
- 1920, Karel CAPEK (1890–1938) “Rossum’s Universal Robots” R.U.R., Praga. Written in 1920, played for the first time in 1921, published in English in 1923.
- His brother Josef proposed the word robot from robotnik that means “slave”.

FIG. 1. The original “play bill” for R.U.R. in Prague, 1921.

Introduction: Automata

ORIGINS OF THE WORD «ROBOT»

- Rossum, a physiologist, try to imitate the Nature and build a biological robot
- the son, an engineer, improves the production process;
- the industrial managers, made aware from his girlfriend, make the robot capable to feel emotions;
- Robots become intolerant and rebel against the human race, killing everyone but the maintenance worker;
- The secret to creating the robots is lost.



Introduction: Automata

ORIGINS OF THE WORD «ROBOT»

- Major idea: the arrogance of men usurping God's role. Rossum’s son says:
  - *“... The product of an engineer is technically at a higher pitch of perfection than a product of nature.”* and
  - *“... God hasn't the least notion of modern engineering.”*
- No mechanic system are proposed, only automata similar to human beings.

FIG. 2. The original robots (actors) from the Prague cast.

Introduction: Neural plasticity

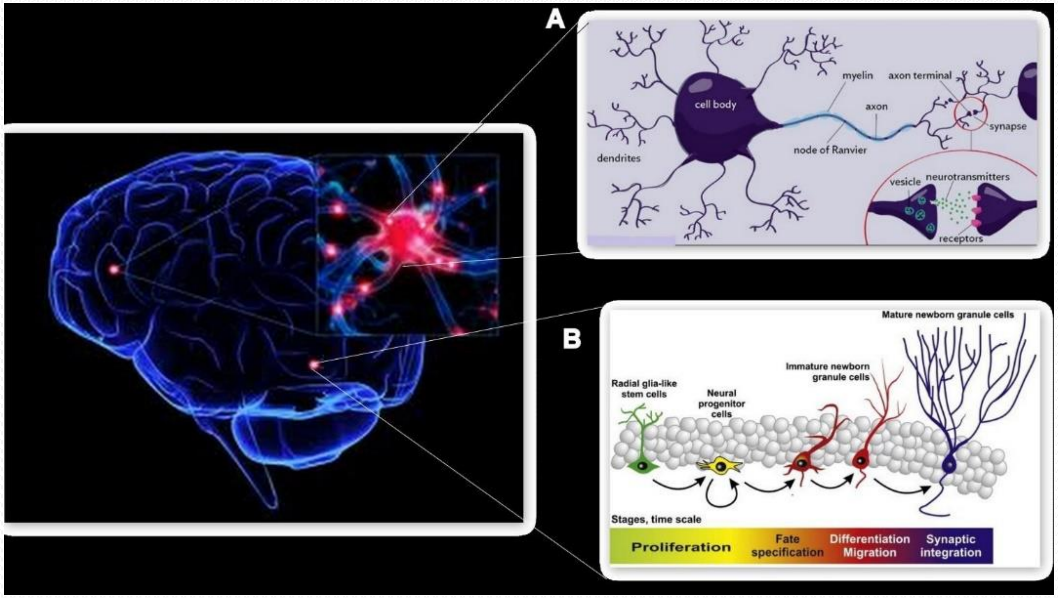
Rehabilitation from stroke is a practice for promoting brain plasticity

Two forms of brain plasticity have been documented:

A.Synaptic plasticity

"*neurons that fire together, wire together*" *(D.Hebb)*

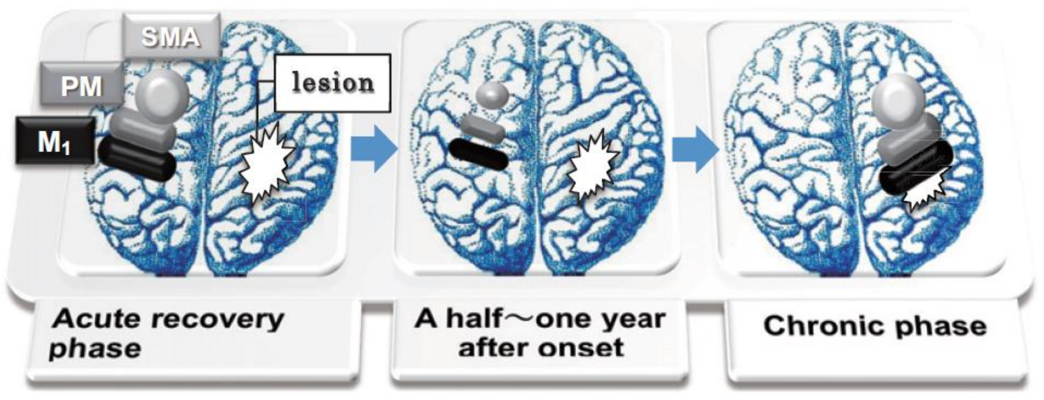
B.Adult neurogenesis



Introduction: Neural plasticity

Cortical activation map changes after stroke

After training periods, diverse areas can activate new synapses to compensate for those lost in the infarction lesion.



New areas involve both:

Ipsilateral areas surrounding the lesion
Contralateral in the related area of the lesion

Introduction: Robots for Rehabilitation

Repetitive tasks have been shown to be effective in regaining motor function

Robotic devices can allow patients to explore a wide and controlled set of "mechanical impedances"

Clockwise from upper left: MIT/IMT-Manus, GENTLE/s, REO-GO, and Armeo Power

Introduction: Robot? What does it means?

- “A robot is a re-programmable, multi-functional, manipulator designed to move material, parts, or specialized devices through variable programmed motions for the performance of a task.” Robotics Industry Association (1980)
- “Robotics is the intelligent connection of perception to action.” Michael Brady (1985)
- “The application of electronic, computerized control systems to mechanical devices designed to perform human functions” Kwakkel G, Kollen BJ, Krebs HI (1997)
- “mechanical device that sometimes resembled a human and was capable of performing a variety of often complex human tasks on command or by being programmed in advance, or a machine or device that operated automatically or by remote control” The American heritage dictionary of the English language. 4th edition. Boston: Houghton Mifflin (2006).

Introduction: Robot Mediated Therapy? Why?

An individual's capacity to move is necessary to perform basic activities of daily living (ADL). Movement disorders significantly reduce a patient's quality of life. Disorders of the upper extremities specifically limit the independence of affected subjects.

Positive outcome of physical rehabilitation, depends heavily on:

- onset,
- duration,
- intensity and
- task orientation of the training, as well as
- the patient's health condition, attention and effort.

Maciejasz et al. Journal of NeuroEngineering and Rehabilitation 2014

Introduction: Robot Mediated Therapy? Why?

Intense repetitions of coordinated motor activities constitute a significant burden for the therapists assisting patients.

The duration of primary rehabilitation is getting shorter and shorter. These problems will probably exacerbate in the future as life expectancy continues to increase accompanied by the prevalence of both moderate and severe motor disabilities in the elderly population and consequently increasing their need of physical assistance.

Maciejasz et al. Journal of NeuroEngineering and Rehabilitation 2014

Introduction: Robot Mediated Therapy? Why?

Rehabilitation is defined as a dynamic process of planned adaptive change in lifestyle in response to unplanned change imposed on an individual by disease or traumatic incident.

The success of depends on:

- appropriate timing,
- patient selection,
- choice of rehabilitation program,
- continued medical management, and
- appropriate discharge planning.

Gunasekera, W.S.L. and J. Bendali, Rehabilitation of Neurologically Injured Patients, in Neurosurgery. 2005, Springer. p. 407-421.

Introduction: Robot Mediated Therapy? Why?

Rehabilitation incurs considerable costs to health care systems all over the world.

- Brain injuries,
- movement disorders and
- chronic pain

affect hundreds of thousands of people worldwide and have a profound impact in their quality of life.

Strokes are the third most common cause of death worldwide after heart disease and cancer, and the most common cause of acquired physical disability.

This in turn poses diverse challenges to health services and rehabilitation centres as the individual experiences emotional discomfort in addition to psychological trauma and reduced mobility.

Adriano O. Andrade, Bridging the gap between robotic technology and health care, in Biomedical Signal Processing and Control 10 (2014) 65–78.

Introduction: Robot Mediated Therapy? Why?

Rehabilitation robotic systems are best suited:

- to perform labor-intensive or tedious activities, such as guiding thousands of repetitive movements:
  - replicating some features of a therapist’s manual assistance,
  - allowing patients to semi autonomously practice their movement training,
- to support and facilitate movements that are:
  - unsafe or difficult to perform with manual assistance,
  - beyond the capabilities of therapists in terms of speed, sensing, strength, and repeatability of the mobilization exercises.

Introduction: Robot Mediated Therapy? Why?

Rehabilitation robotic systems are:

- ***patient-specific*** → optimize the degree of involvement of the patient by customizing the level of physical and/or cognitive assistance provided during each therapeutic session.
- ***self-motivating*** → give direct quantitative feedback to the patient about her/his performance during and after the therapy (self-appraisal).
- ***prone to telemedicine application***.

Introduction: Robot Mediated Therapy? Why?

Rehabilitation robotic systems:

- incorporates a user interface that helps visually orient movements to targets,
- provides feedback on performance,
- can allow quantitative monitoring of progress.

Rehabilitation robotic systems require:

- new developments on actuators,
- new techniques for controlling classical actuators,
- new safety designs.

Introduction: Robot Mediated Therapy? Why?

PROS AND CONS

- While Robot Mediated Therapy (RMT) can be a valuable tool to facilitate intensive movement practice in a motivating and engaging environment, success of therapy also depends on self-administered therapy beyond hospital stay.
- Efforts to strengthen the physio-therapist's skills.
- Robotic technologies are advanced tools and not a physiotherapist replacement.
- One advantage of robotic therapy over conventional therapy is that robots allow therapists to take a step back from physically engaging in assisting the patient to perform repetitive movements.
- The robot can allow therapists the opportunity to observe, make informed decisions on best course of action and manage more patients.

Adriano O. Andrade, Bridging the gap between robotic technology and health care, in Biomedical Signal Processing and Control 10 (2014) 65–78.

Introduction: Robot Mediated Therapy? Why?

FUTURE TRENDS

- A recent review has concluded that despite mounting evidence suggesting robotic therapies are not more likely to improve patients' activities of the daily living than any other therapy, it has shown great capacity to improve patients' motor function and core strength.
- The consensus exists that equal importance should be placed by clinicians and researchers working in the field in establishing guidelines on the study design and assessment and on pushing for more efficient, safer and inexpensive technologies.
- A hospital or clinical environment might use devices able to retrain a variety of movements over a large percentage of the normal range of human movements.
- …

Adriano O. Andrade, Bridging the gap between robotic technology and health care, in Biomedical Signal Processing and Control 10 (2014) 65–78.

Introduction: Robot Mediated Therapy? Why?

FUTURE TRENDS

- …
- However, an emphasis should be placed on allowing the implementation of therapies resembling activities of the daily living such as, picking up a book after reading at a table top and placing it on a bookshelf.
- There is a need for more effective tools so that neurotherapies can be moved away from the therapy gymnasium and into the person's home. These tools have the potential to make a large impact on the recovery of people following their stroke, as therapy will be available on demand at the convenience and in a familiar environment to the patient.
- As part of this therapy process we can exploit the dual nature of robotic devices to both assist and measure movement.

Adriano O. Andrade, Bridging the gap between robotic technology and health care, in Biomedical Signal Processing and Control 10 (2014) 65–78.

Introduction: Robot Mediated Therapy? Why?

THE BARRIERS TO THE ACCEPTABILITY

The barriers to the acceptability of a new technology-based treatment/service in healthcare can be classified in:

- **Technological**: consists in patient's unwillingness to learn the procedure needed.
- **Behavioral**: comprises fear of innovation, distrust and concern about personal data privacy .
- **Organizational**: physicians' resistance to change.
- **Economical**: is represented by costs of the procedure and incapability of experimenters to demonstrate cost-saving or clinical benefits to the patient.
- …

S.Mazzoleni, Acceptability of robotic technology in neuro-rehabilitation: Preliminary results on chronic stroke patient computer methods and programs in biomedicine 2014

Introduction: Robot Mediated Therapy? Why?

THE BARRIERS TO THE ACCEPTABILITY

- …

In particular, the older population has greater difficulty to use and accept new technologies. The older adults are sometimes unaware of the benefits coming from the use of new technologies. It is necessary to overcome these barriers for the adoption of new technology-based treatments/services.

- three tactical avenues:
  - i. widely explain procedures and minimize training;
  - ii. clearly expose potential benefits to the patient; and
  - iii. fully explain confidentiality of the information provided.

S.Mazzoleni Acceptability of robotic technology in neuro-rehabilitation: Preliminary results on chronic stroke patient computer methods and programs in biomedicine 2014

1. Introduction on robot mediated therapy

2. Rehabilitation robotic systems

3. Effectiveness

4. Robot mediated therapy @SAPIENZA

Rehabilitation robotic systems: Categorization?

TRAINING

I. Unilateral or
II. Bilateral

movements

OPERATING PRINCIPLE

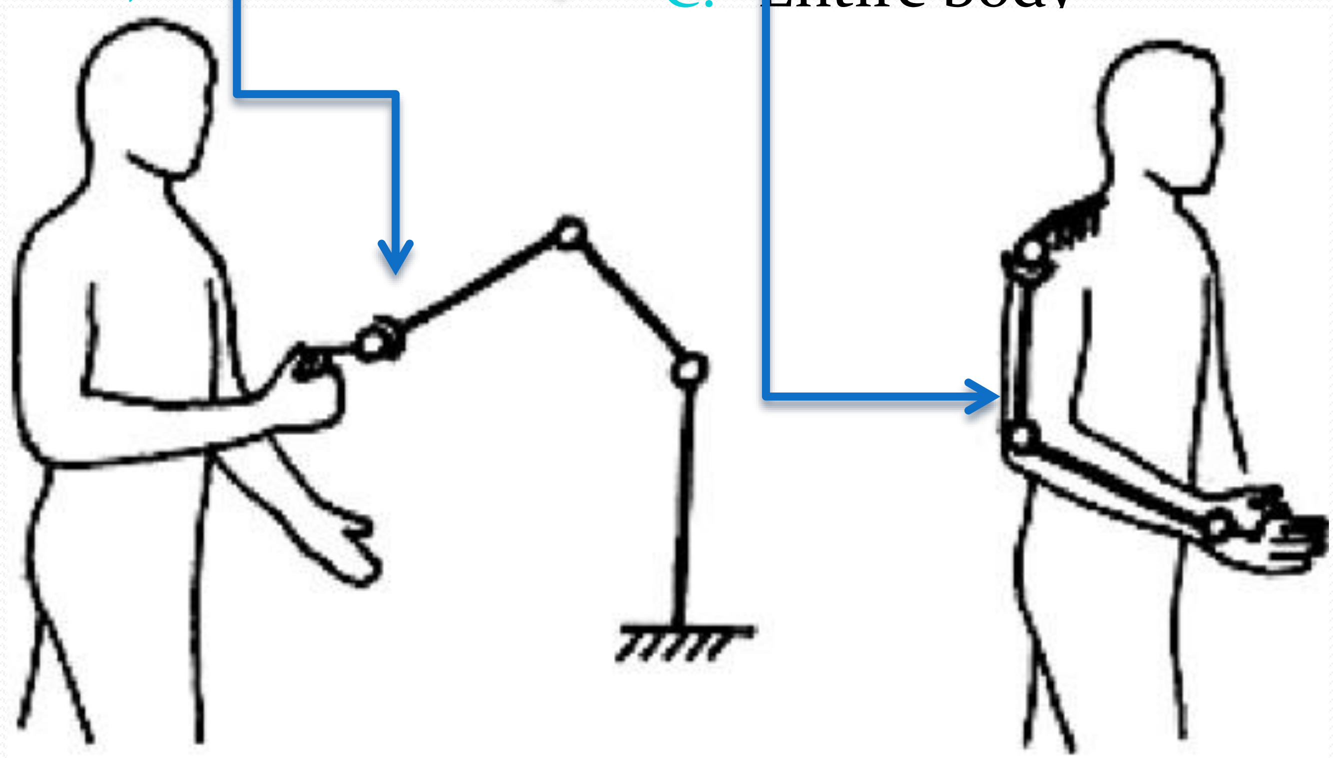
a) End-effector;
b) Exoskeleton

LIMB

A. Upper
B. Lower
C. Entire body

DEVICE

i. Active
ii. Passive
iii. Haptic
iv. Coaching



(a) (b)

Rehabilitation robotic systems: Categorization?

GLOSSARY OF TERMS CONCERNING TYPE OF ASSISTANCE

- **Active device**: A device able to move limbs. Under such condition, this device requires active actuators which may increase the weight. It may also apply to subjects completely unable to move their limb.
- **Passive device**: A device unable to move limbs, but may resist the movement when exerted in the wrong direction. This type of device may only be used for rehabilitation of subjects able to move their limbs. It is usually lighter than active device since it possesses no actuators other than brakes.
- …

Rehabilitation robotic systems: Categorization?

GLOSSARY OF TERMS CONCERNING TYPE OF ASSISTANCE

- …
- **Haptic device**: A device that interfaces with the user through the sense of touch. In most cases it provides some amount of resistive force, often also some other sensation (e.g. vibration). It is sometimes also able to generate specific movements. However, the force it generates is usually small. Haptic devices are commonly used in rehabilitation settings with virtual environments.
- **Coaching device**: A device that neither assists nor resists movement. However, it is able to track the movement and provide feedback related to the performance of the subject. As haptic devices, coaching devices are also commonly used in rehabilitation settings with virtual environments.

Rehabilitation robotic systems: Categorization?

GLOSSARY OF TERMS CONCERNING TYPE OF ASSISTANCE

- **Active exercise**: An exercise in which subjects actively move their limb, although some assistance of the device may be provided. Such type of the exercise may be performed using any of the above listed types of devices.
- **Passive exercise**: An exercise in which the subject remains passive, while a device moves the limb. This type of exercise requires an active device. Continuous Passive Motion (CPM) training is an example of passive exercise with active devices.

Rehabilitation robotic systems: Categorization?

GLOSSARY OF TERMS CONCERNING MECHANICAL DESIGN OF ROBOTS FOR REHABILITATION

- **End-effector based device**: Contacts a subject's limb only at its most distal part. It simplifies the structure of the device. However, it may complicate the control of the limb position in cases with multiple possible degrees of freedom.
- **Exoskeleton-based device:** A device with a mechanical structure that mirrors the skeletal structure of the limb, i.e. each segment of the limb associated with a joint movement is attached to the corresponding segment of the device. This design allows independent, concurrent and precise control of movements in a few limb joints. It is, however, more complex than an end-effector based device. Orthoses restricting or assisting movement in one or more joints may be also considered exoskeleton-based devices.
- …

Rehabilitation robotic systems: Categorization?

GLOSSARY OF TERMS CONCERNING MECHANICAL DESIGN OF ROBOTS FOR REHABILITATION

- …
- **Planar robot**: A device, usually end-effector based, moving in a specific plane. Design of planar robots, decreases costs as well as the range of movements that may be exercised. Although this device performs movements in a plane, joints of the limb may still move in a three-dimensional space.
- **Back-drivability**: A property of mechanical design indicating that the patient is able to move the device, even when the device is in passive state. It increases patient safety, because it does not constrain limb movements and keeps patient's limb in a comfortable position.
- …

Rehabilitation robotic systems: Categorization?

GLOSSARY OF TERMS CONCERNING MECHANICAL DESIGN OF ROBOTS FOR REHABILITATION

- …
- **Modularity**: A property of a device indicating that optional parts may adapt it to a specific condition or simply to perform additional exercises.
- **Reconfigurability**: A property of a device indicating that its mechanical structure may be modified without adding additional parts in order to adapt it to the condition of the subject or to perform other form of training.

Rehabilitation robotic systems: Categorization?

GLOSSARY OF TERMS CONCERNING CONTROL STRATEGY OF ROBOTS FOR REHABILITATION

- **“High-level” control strategy**: A control strategy with control algorithms explicitly designed to induce motor plasticity.
- **Assistive control**: A “high-level” control strategy in which a device provides the physical assistance to aid the patient in accomplishing an intended movement.
- **Challenge-based control**: A “high-level” control strategy in which a device challenges the patient to accomplish an intended movement.
- **Haptic stimulation**: A “high-level” control strategy in which a robotic device is used as a haptic interface to perform activities in virtual reality environment.
- **Couching control**: A “high-level” control strategy in which a robotic device neither physically assists nor resists the movement of the subject. It only quantifies and provides feedback (visual, acoustic or other) concerning the performance of the subject during exercise.
- …

Rehabilitation robotic systems: Categorization?

GLOSSARY OF TERMS CONCERNING CONTROL STRATEGY OF ROBOTS FOR REHABILITATION

- …
- **"Low-level" control strategy**: A control strategy considered in the implementation of the "high-level" control strategy in a device by appropriate control of the force, position, impedance or admittance.
- **Admittance control**: A "low-level" control strategy in which the force exerted by the user is measured, and the device generates the corresponding displacement.
- **Impedance control**: A "low-level" control strategy in which the motion of the limb is measured and the robot provides the corresponding force feedback.
- …

Rehabilitation robotic systems: Categorization?

CLASSIFICATION OF CLINICAL TRIALS OF REHABILITATION ROBOTS

- **Category 0 Initial feasibility studies**: Trials performed with low number of healthy volunteers, often using the prototype of a device, in order to evaluate its safety and clinical feasibility.
- **Category I Pilot Consideration-of-Concept studies**: Clinical trials aimed at testing device safety, clinical feasibility and potential benefit. They are performed in a small population of subjects suffering from the target disease. There is either no control group in the trial, or healthy subjects are used as control.
- …

Rehabilitation robotic systems: Categorization?

CLASSIFICATION OF CLINICAL TRIALS OF REHABILITATION ROBOTS

- …
- **Category II Development-of-Concept studies**: Clinical studies aiming at verification of device efficacy. Include a standardized description of the intervention, a control group, randomization and blinded outcome assessment.
- **Category III/IV Demonstration-of-Concept-Studies/Proof-of-Concept studies:** Further evaluation of the device efficacy. Similar to category II, however, usually these are multicentered studies with high number of participants.

Rehabilitation robotic systems: Categorization?

120 devices for the upper limb (end-effector & exoskeleton)

Maciejasz et al A survey on robotic devices for upper limb rehabilitation Journal of NeuroEngineering and Rehabilitation 2014, 11:3

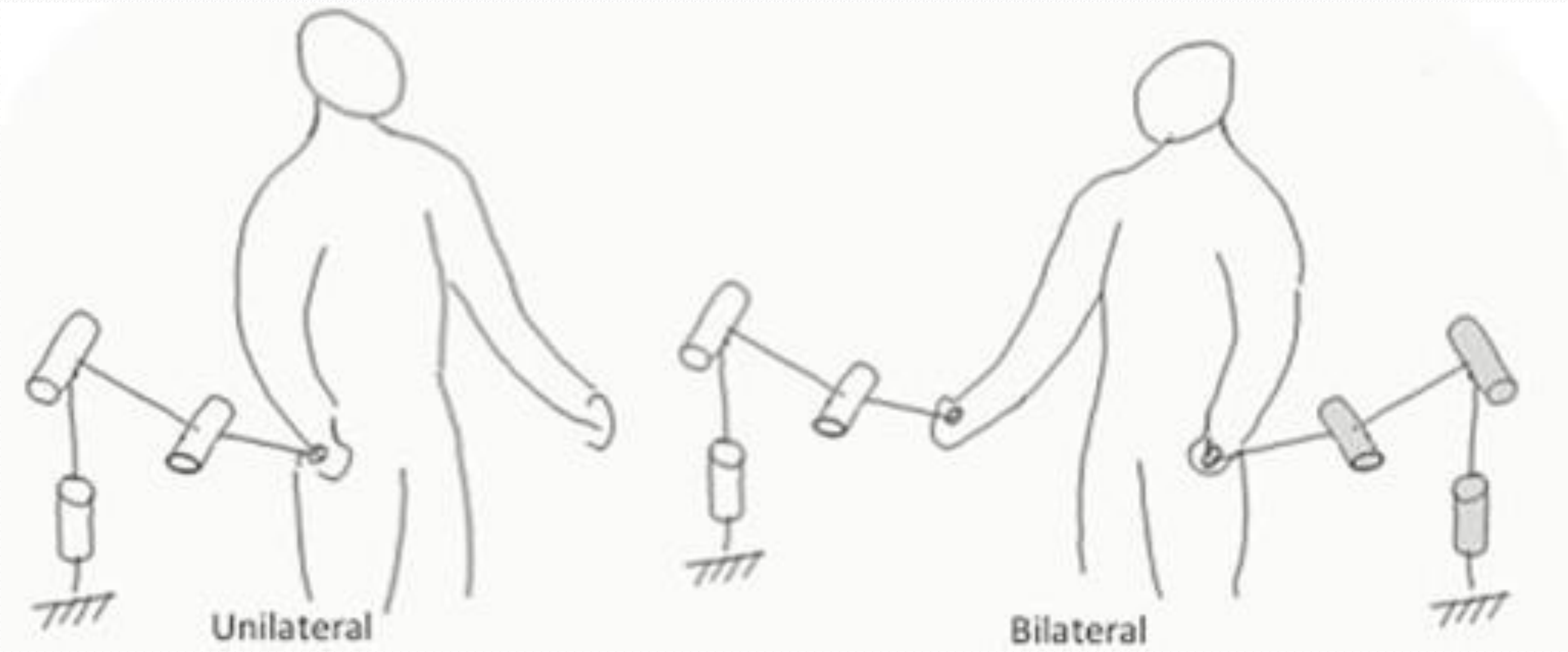
OPERATING PRINCIPLE → **LIMB** → **REHAB or TELEREHAB**

- **Rehabilitation robotic systems**
  - end-effector
    - upper limb
      - local
      - remote
    - lower limb
      - local
      - remote
  - exoskeleton
    - upper limb
    - lower limb
    - upper & lower limb

Rehabilitation robotic systems: End-effector robot?

- End-effector robots hold the patient's limb at one point and generate forces at the interface.
- The joints of end-effector robots do not match with that of the human limb.

Lo H.S., Xie S.Q. Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects Medical Engineering & Physics 34(3), 261-268, 2012



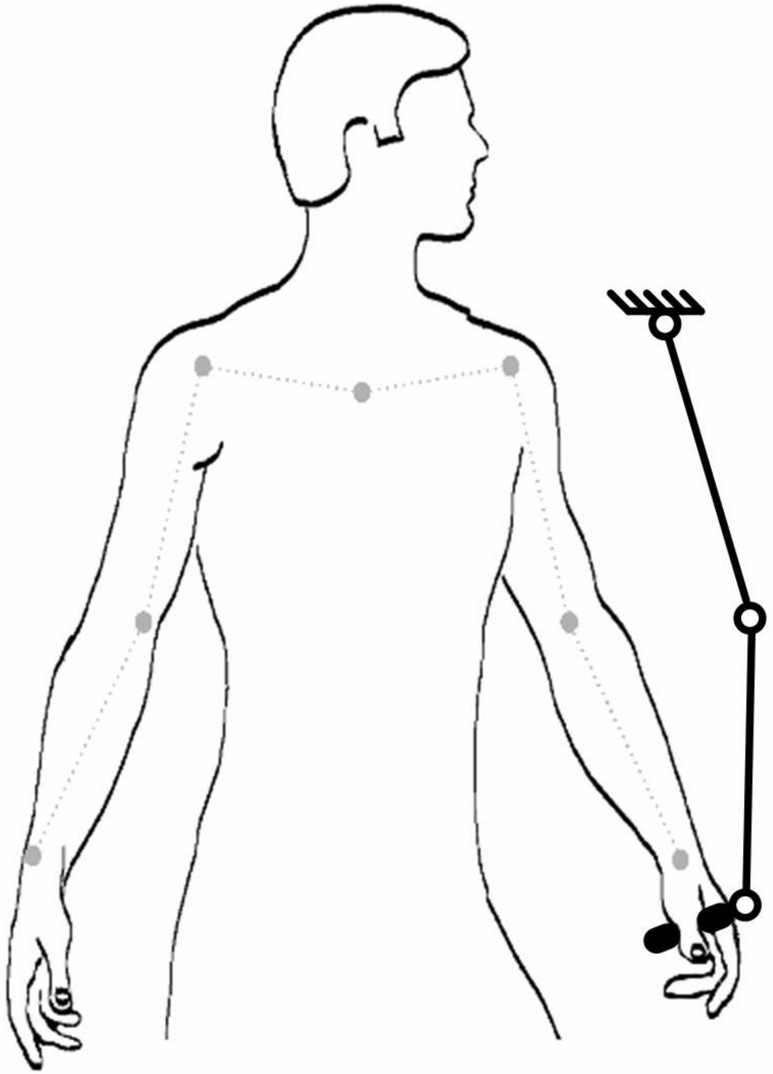
Rehabilitation robotic systems: End-effector robot?

PROS

- simpler,
- easier to fabricate and
- can be easily adjusted to fit different patient arm lengths.

CONS

- Kinematics evaluated with simplification,
- controlling the torque at specific limb joints is not possible,
- the range of motion tends to be limited.

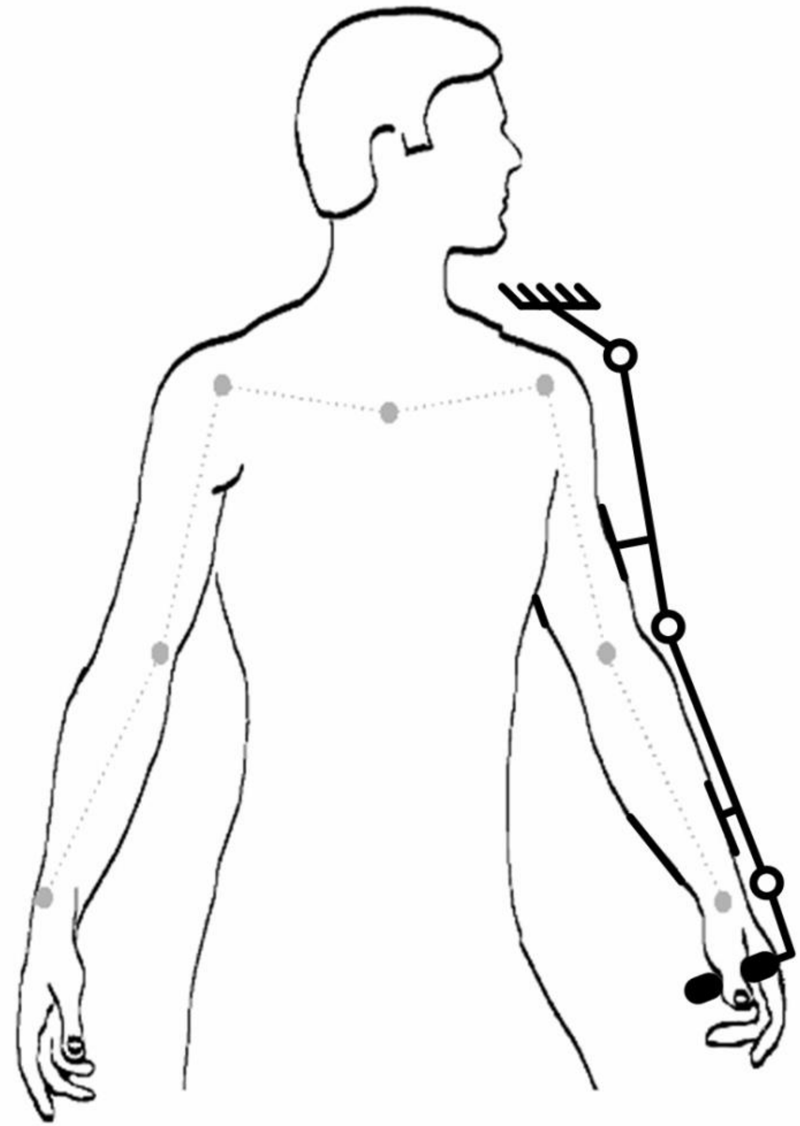


Lo H.S., Xie S.Q. Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects Medical Engineering & Physics 34(3), 261-268, 2012

Rehabilitation robotic systems: Exoskeletons?

BOUNDARY CONDITIONS

- a structure which resembles the human upper or lower limb,
- robot joint axes that match the limb joint axes,
- designed to operate side by side with the human limb,
- attachable to the limb at multiple locations.



Lo H.S., Xie S.Q. Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects Medical Engineering & Physics 34(3), 261-268, 2012

Rehabilitation robotic systems: Exoskeletons?

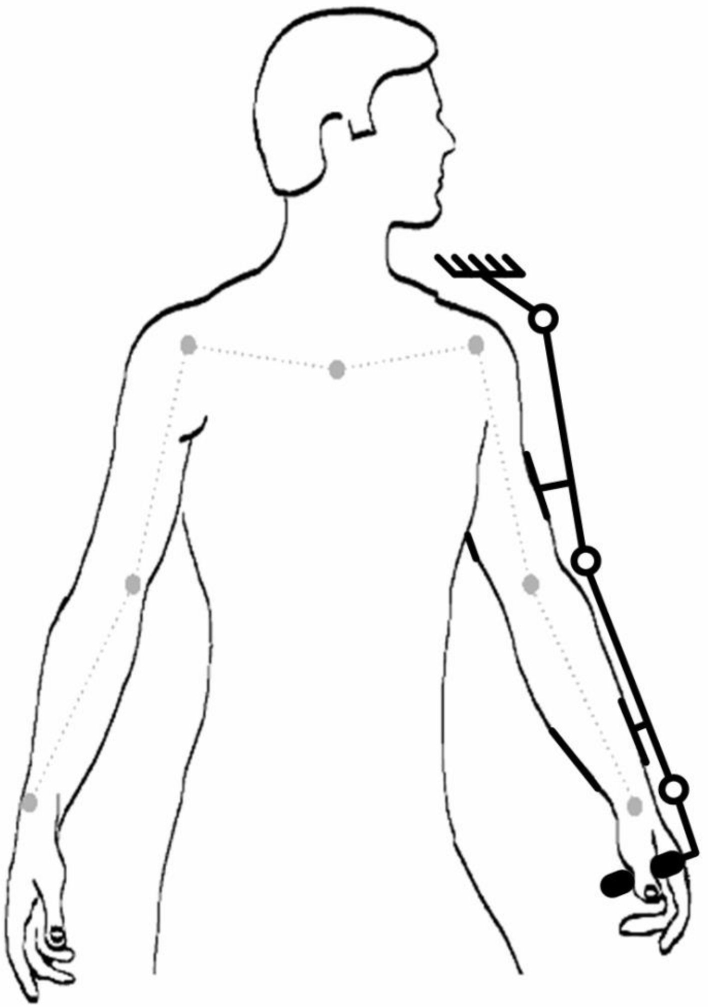
PROS

- fully determine the upper limb posture and controlled torques to be applied to each joint separately.
- target specific muscles for training by generating a calculated combination of torques at certain joints.
- a larger range of motion may be possible compared to end-effector robots.

CONS

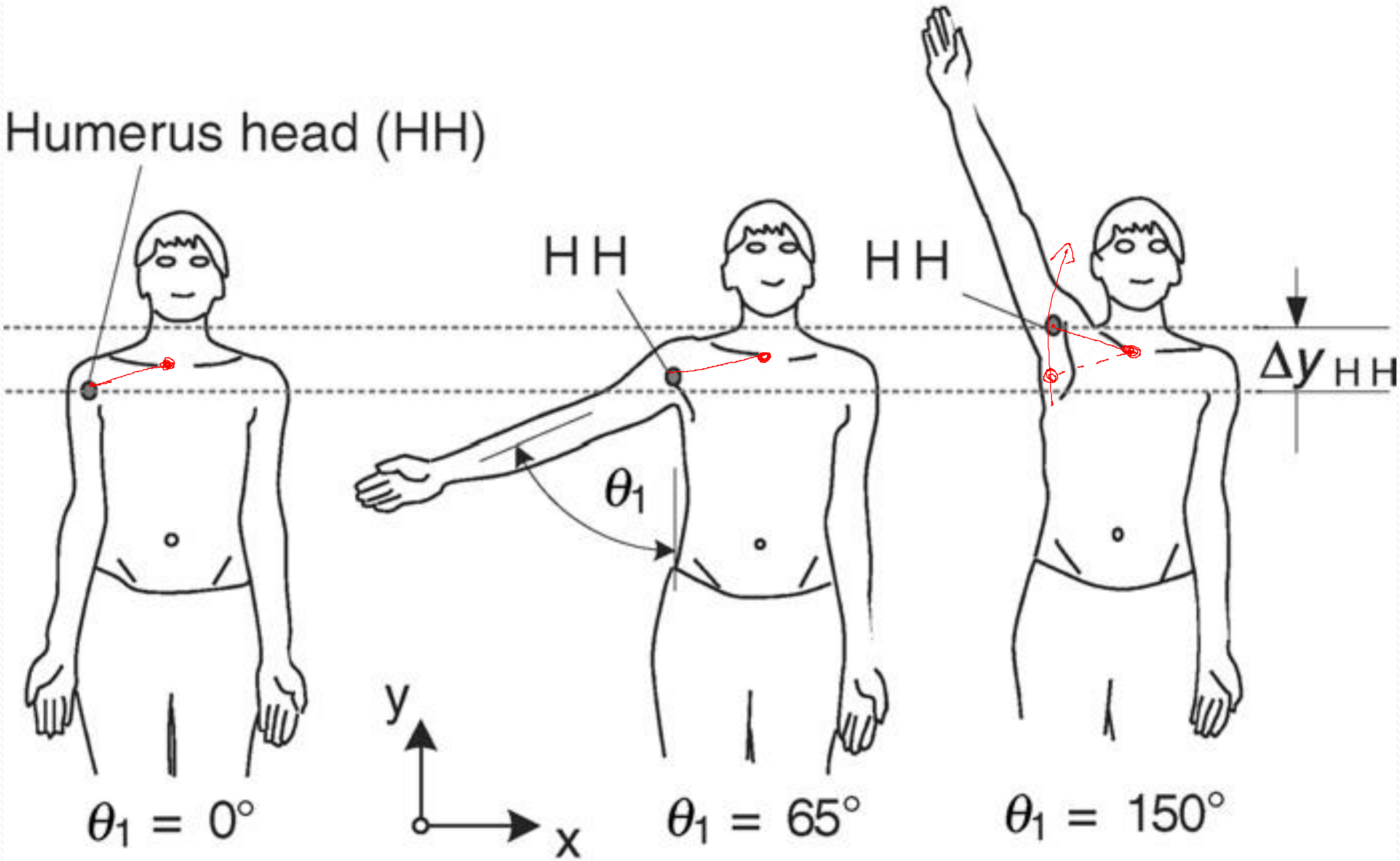
- Much more complex design → costly.

Lo H.S., Xie S.Q. Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects Medical Engineering & Physics 34(3), 261-268, 2012



Rehabilitation robotic systems: Alignment between exoskeleton and human joints?

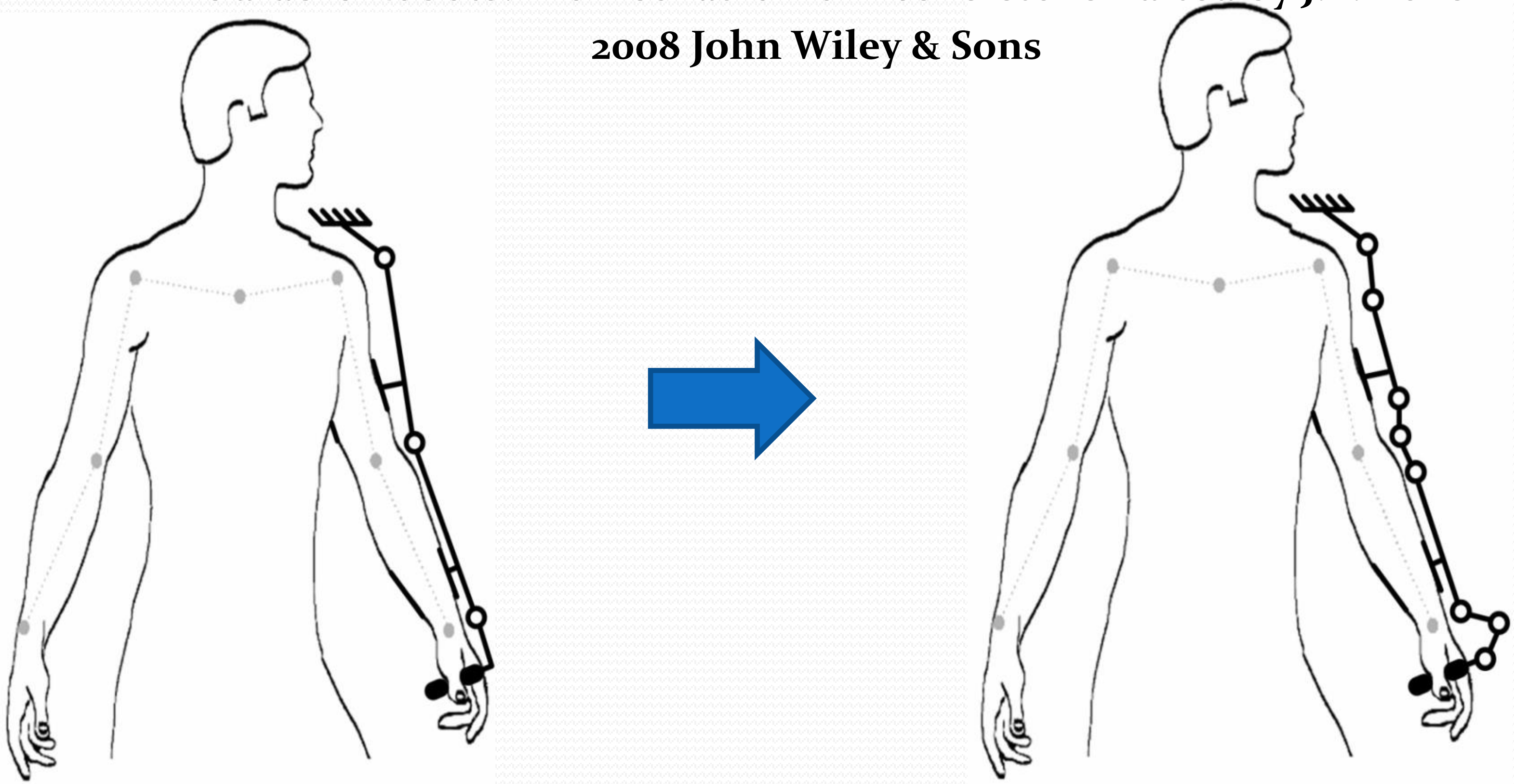
A difficult task! Undesired reaction forces can otherwise be created in the human joints by a kinematic mismatch



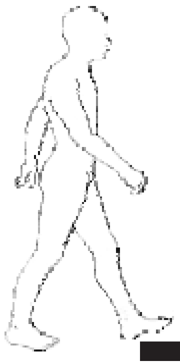
Rehabilitation robotic systems: Alignment between exoskeleton and human joints?

To improve the fit between the human limb and the robotic device, a class of exoskeletons is being developed with a more complex structure with multiple degrees of redundancy to cope with interaction.

We arable Robots: Biomechatronic Exoskeletons Edited by J.L. Pons 2008 John Wiley & Sons



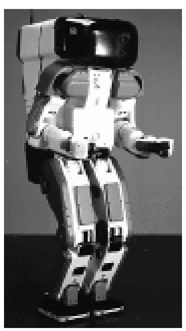
Rehabilitation robotic systems: Are the exoskeletons efficient?



Energy consumption during bipedal walking: the energy consumption of gait per unit of distance travelled by a human (for the optimal walking speed) and by an old robot (Honda P2)

Human (1400 m/slice of bread)

Mechanical cost of transport



Robot, P2 Honda (31 m/slice of bread)

Aims of the exoskeleton:

- reduction of the wearer's metabolic energy expenditure,
- and minimization of the energy requirements for actuating the exoskeleton.

Rehabilitation robotic systems: Therapies?

STRENGTH THERAPY:

- robots apply a resistive load to impede the users' movement to improve muscle strength.

MOTION THERAPY:

- passive,
- active-assist and
- active exercises.

It requires a different level of participation from patients ranging from no active effort in the passive exercises to full users driven motion in active exercises.

- Perturbing a movement, for example by applying an external force, renders it more difficult to perform. Increased difficulty adds to the intensity of training and could serve as a stronger learning stimulus.

Rehabilitation robotic systems: Devices?

- **Active device:** A device able to move limbs. Under such condition, this device requires active actuators which may increase the weight. It may also apply to subjects completely unable to move their limb.
- **Passive device:** A device unable to move limbs, but may resist the movement when exerted in the wrong direction. This type of device may only be used for rehabilitation of subjects able to move their limbs. It is usually lighter than active device since it possesses no actuators other than brakes.
- …

Maciejasz et al A survey on robotic devices for upper limb rehabilitation Journal of NeuroEngineering and Rehabilitation 2014, 11:3

Rehabilitation robotic systems: Devices?

- …
- **Haptic device:** A device that interfaces with the user through the sense of touch. In most cases it provides some amount of resistive force, often also some other sensation (e.g. vibration). It is sometimes also able to generate specific movements. However, the force it generates is usually small. Haptic devices are commonly used in rehabilitation settings with virtual environments.
- **Coaching device:** A device that neither assists nor resists movement. However, it is able to track the movement and provide feedback related to the performance of the subject. As haptic devices, coaching devices are also commonly used in rehabilitation settings with virtual environments.

Maciejasz et al A survey on robotic devices for upper limb rehabilitation Journal of NeuroEngineering and Rehabilitation 2014, 11:3

Rehabilitation robotic systems: Devices?

Haptic perception is the process of recognizing objects through touch. It involves a combination of somatosensory perception of patterns on the skin surface (e.g., edges, curvature, and texture) and proprioception of hand position and conformation.

απτεσθαι: to touch

Rehabilitation robotic systems: Devices?

BACK-DRIVEABILITY

The machine is required to have a high transparency, i.e. the ability of being moved by the patient with negligible perturbance of natural motions. This characteristic is addressed as back-driveability.

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

Rehabilitation robotic systems: Controller

Alongside the development of the more sophisticated robotic mechanism, the development of more sophisticate control strategies **that specify how these devices interact with the patients** is also necessary.

The goal of a robotic device for rehabilitation purpose **is to provoke motor plasticity** by means of the selected exercises to be performed by the participants.

No consensus about how this goal can best be achieved

Control algorithms have been designed on *ad-hoc* basis (rehabilitation, neuroscience, and motor learning literature)

Rehabilitation robotic systems: Controller

A possible classification: strategy to provoke plasticity

- **Assistance strategies:** the robot helps participant to move their weakened limbs in desired patterns.
- **Challenge-based strategies:** the device make the task more difficult.
- **Hapting simulation strategies:** practice in virtual environment
- **Embodied coaching strategies:** the robot does not contact the patients, but direct and encourage therapy activities

To different devices correspond different strategies!

Rehabilitation robotic systems: Controller

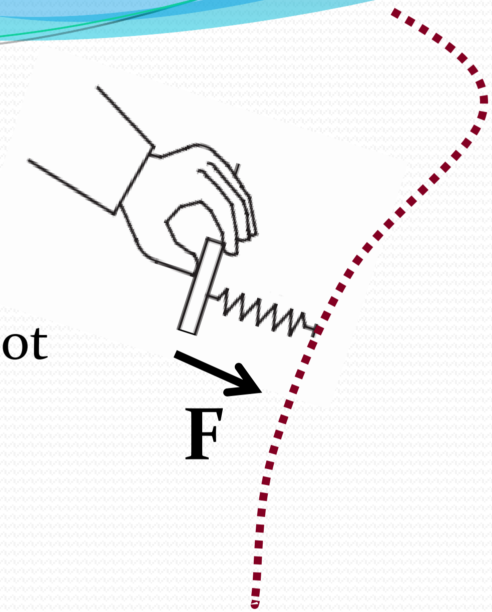
Active assist strategies is the first and the most used control paradigm that has been explored in robotic therapy.

Three different strategies can be identified:

1. Impedance-based assistance;
2. EMG-based assistance;
3. Performance-based adaptation of task parameters.

It is important to claims that these strategies are not mutually independent: in fact, multiple strategies can be used together.

Controller: Impedance-based assistance



PARADIGM:

- the patient moves along a desired trajectory → the robot should not intervene;
- the patients deviates from the desired trajectory → the robot create a restoring force (mechanical impedance)

Force applied by the robot

$$\boldsymbol{F} = B(\dot{\boldsymbol{x}}_d - \dot{\boldsymbol{x}}) + K(\boldsymbol{x}_d - \boldsymbol{x})$$

Where K is the desired stiffness, B is the desired damping, x_d and x are the desired and the actual trajectory, respectively.

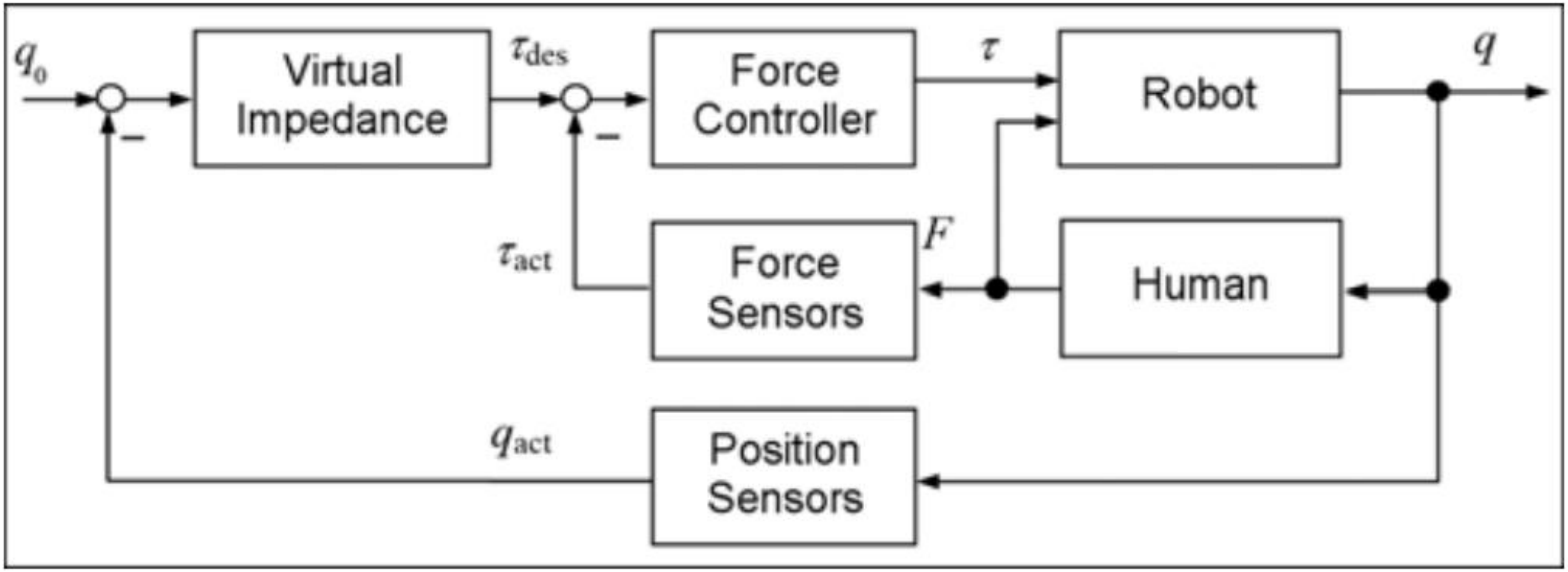
PROS

- A deviation from a given trajectory is allowed
- The magnitude of the force is variable, reducing the risk of injuries

CON

- Fixed-reference trajectory

Controller: Impedance-based assistance



From the concept to the implementation for a 2D reaching task

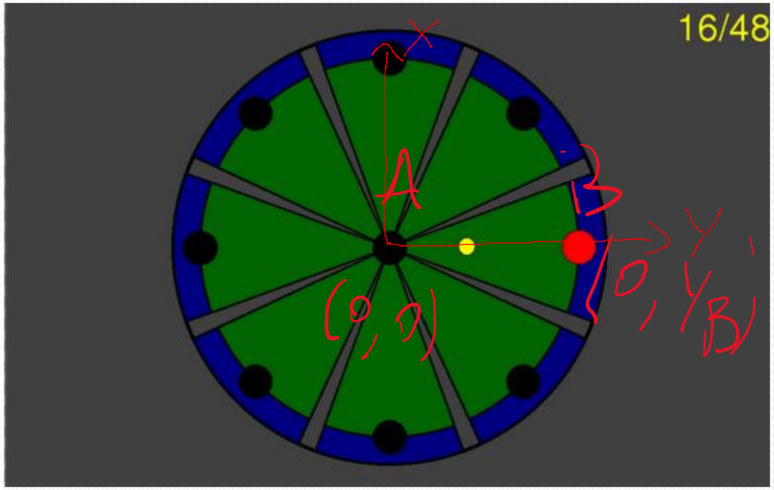
Controller: Impedance-based assistance

From the concept to the implementation for a 2D reaching task

$$F_{c,x} = -kx - b\dot{x}$$

$$F_{c,y} = -k(y - y_{m.j.}) - b\dot{y}$$

$$y_{m.j.} = l_m\left[10\left(\frac{t}{t_m}\right)^3 - 15\left(\frac{t}{t_m}\right)^4 + 6\left(\frac{t}{t_m}\right)^5\right]$$



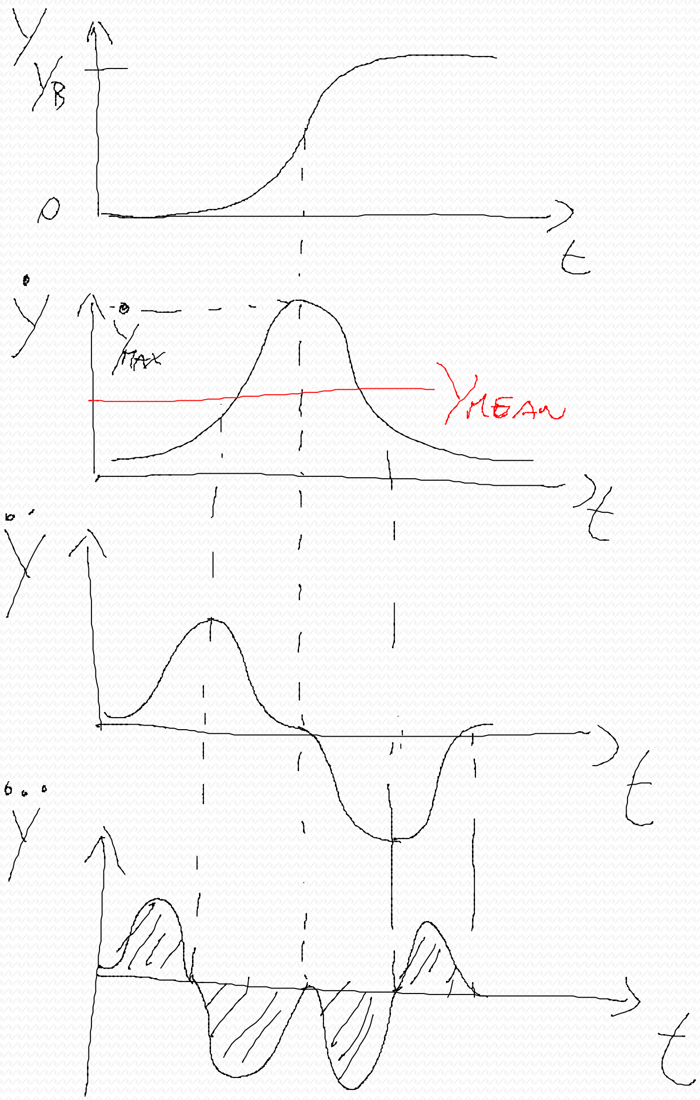
Where:

F	is the force applied by the robot,
ym. j.	is the controller's minimum jerk movement,
k	is the controller stiffness,
b	is the controller damping,
l_m	is the length of movement, and
t_m	is the duration of movement.

The minimum jerk is a model to describe the optimal trajectory in a reaching task.

Krebs et al, (2003), *Autonomous Robots*, 15(1), 7-20.

$A(0,0) \longrightarrow B(0, y_B)$

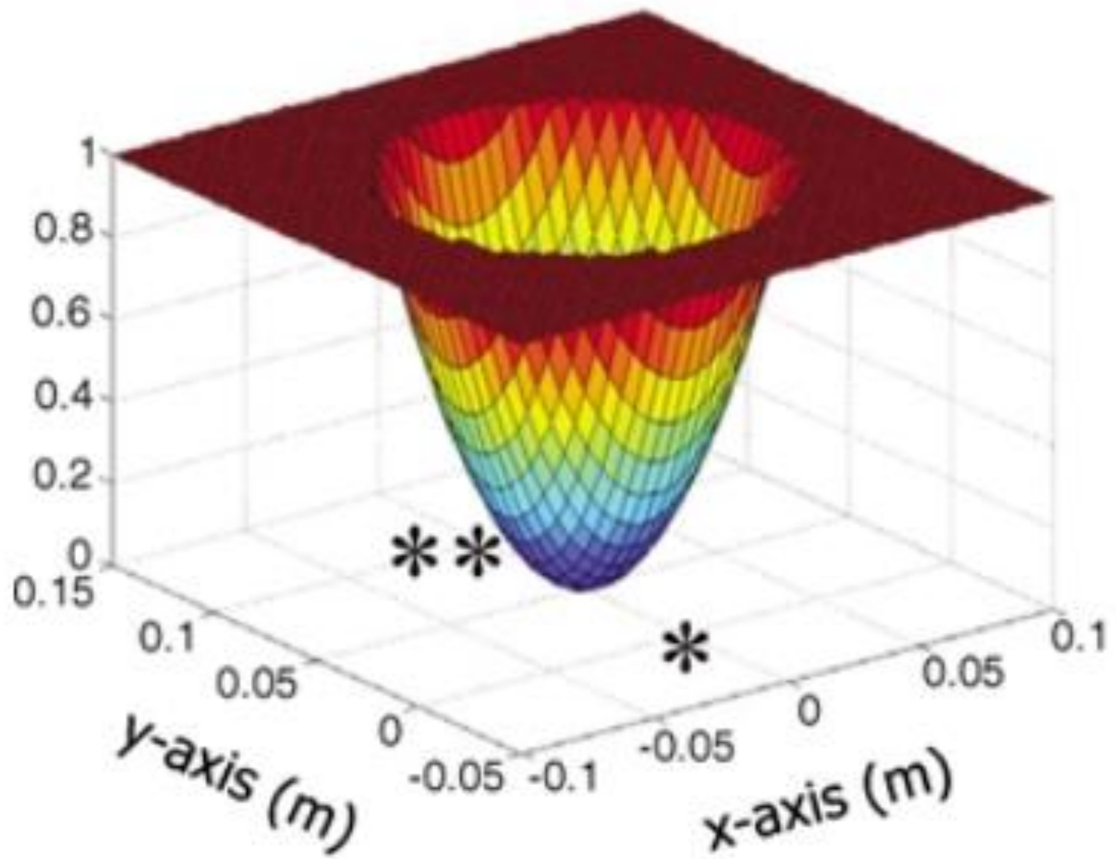


Controller: Impedance-based assistance

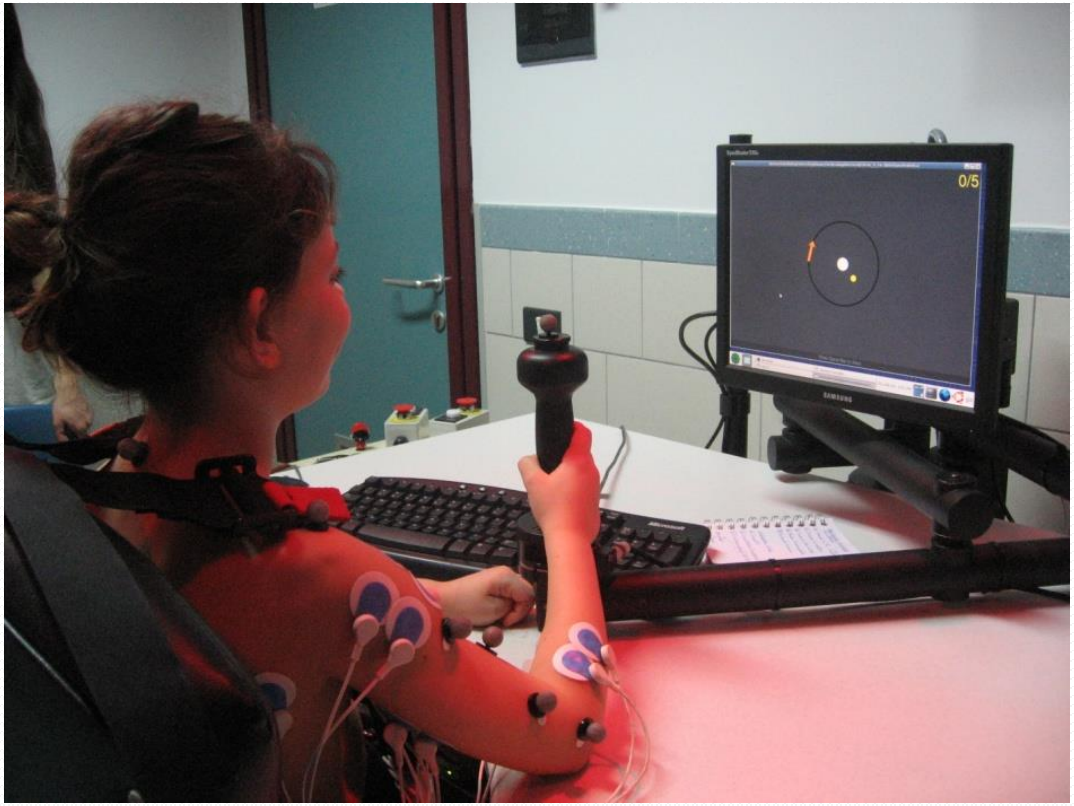
The effect of the stiffness of the controller can be visualized as a potential energy field about a moving desired position that limits deviation along the target axis, y, and its normal axis, x.
The stiffness and damping values are constant

* Is the initial position
** Is the final position

Krebs et al, (2003), *Autonomous Robots*, 15(1), 7-20.

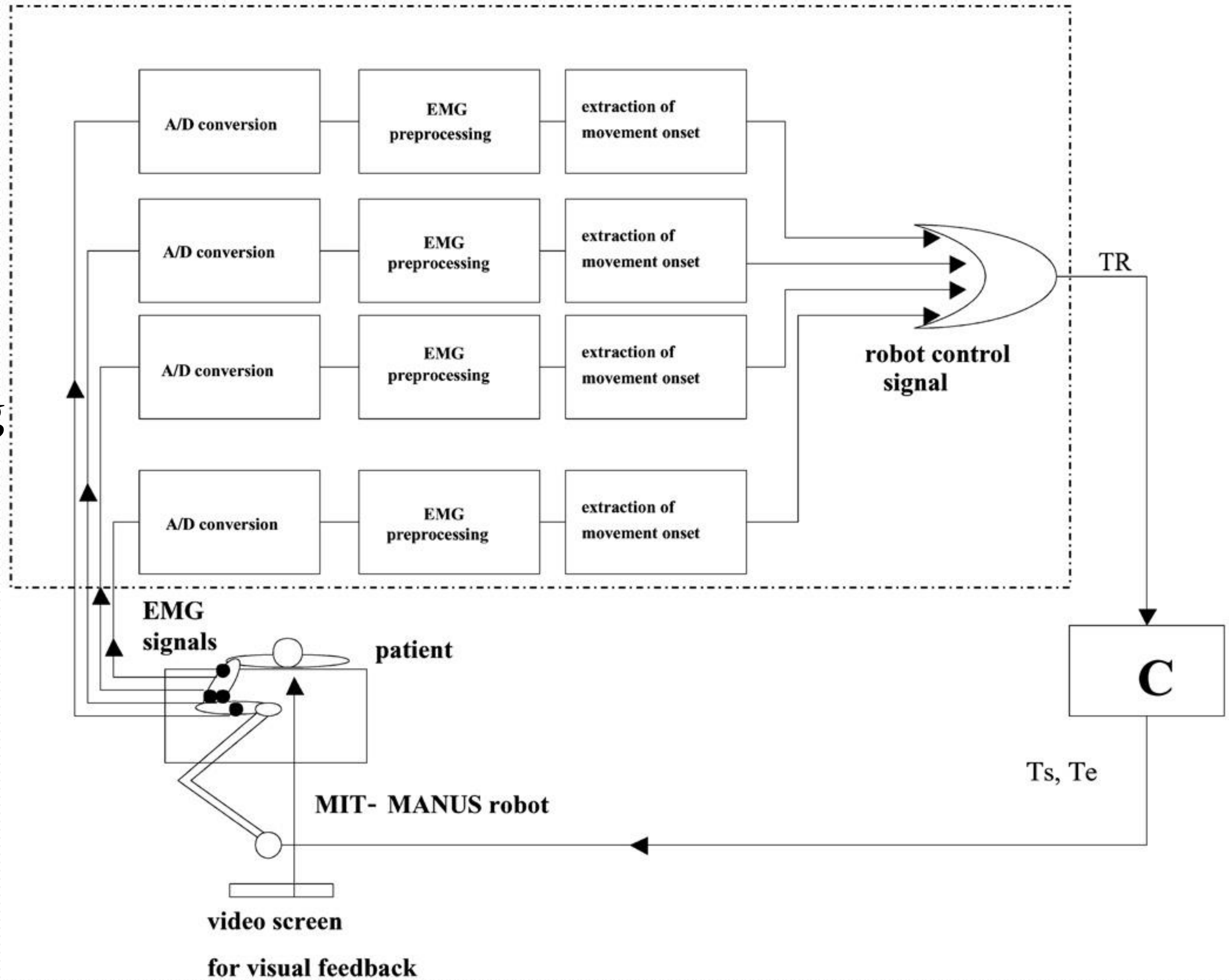


Controller : EMG-based assistance 1/4



EMG-triggered assistance
the robot helps the subject to move the affected limb when the processed EMG signals increased above a threshold.
The onset of a patient’s attempt to move is detected by monitoring EMG in selected muscles, whereupon the robot assists her or him to perform point-to-point movements in a horizontal plane.
Once the robot action had been triggered, the robot impedance controller assisted the patient’s arm movements in the same way as seen before.

Controller : EMG-based assistance 2/4



EMG-triggered assistance

The onset of a patient's attempt to move is detected by monitoring EMG in selected muscles.

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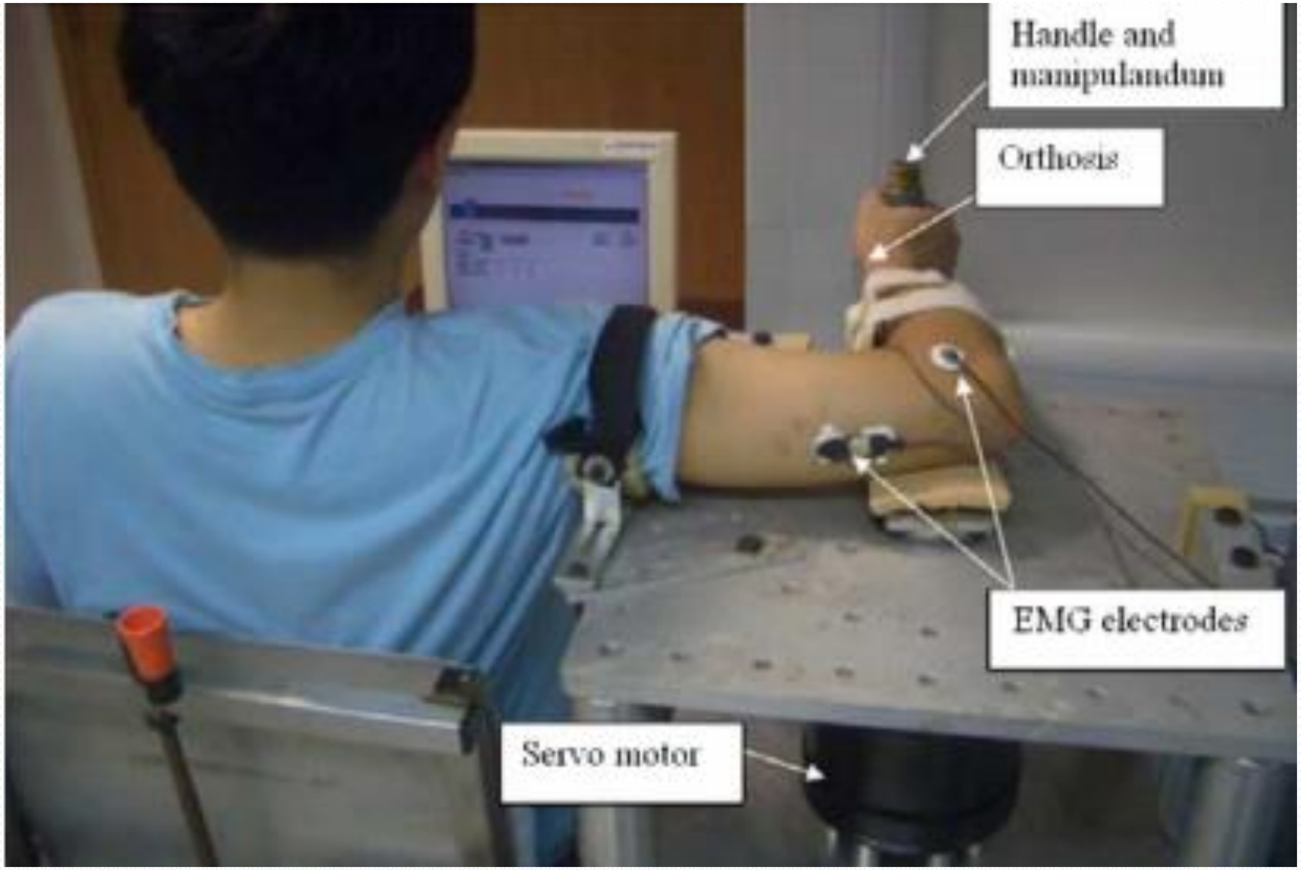
Dipietro et al (2005). Neural Systems and Rehabilitation Engineering, IEEE Transactions on, 13(3), 325-334

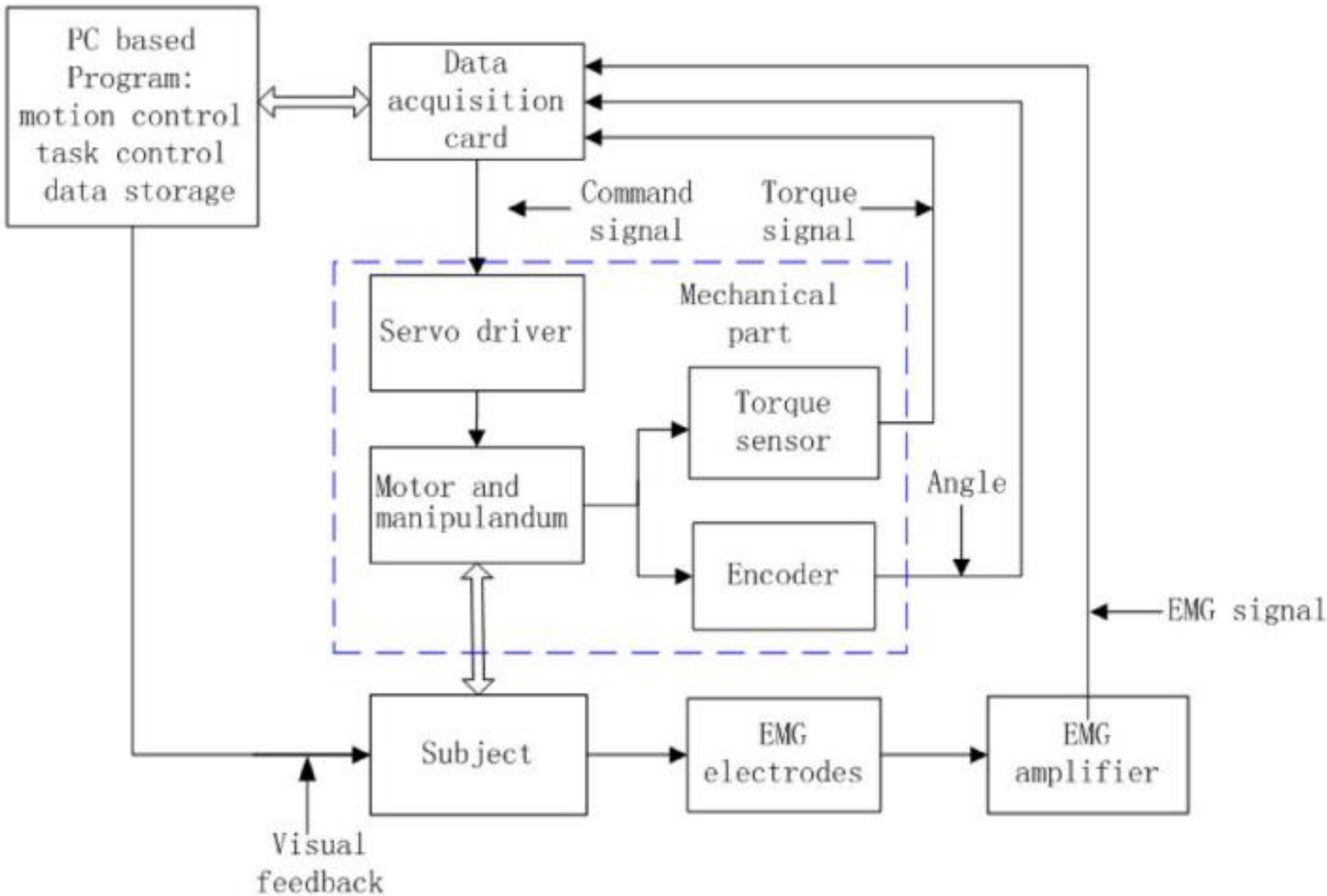
Controller : EMG-based assistance 3/4

Proportional myoelectric control: robot generates forces proportional to the amplitude of the processed EMG signals.



Robotic system with 1 degree-of-freedom developed to assist elbow training in a horizontal plane.

Controller : EMG-based assistance 4/4



The system could provide continuous assistance in extension torque, which was proportional to the amplitude of the subject's EMG signal from the triceps.

Song, et al (2008) ***Neural Systems and Rehabilitation Engineering, IEEE Transactions on,16*(4), 371-379.**

Controller: Performance-based adaptation 1/7

Control strategies that adapt parameters based on online measurement of the participant's performance, to keep the task challenging for the patients. In this way, the difficulties of the task are related to the actual dexterity of the patients (*tailored rehabilitation*). Usually an impedance controller approach is adopted.

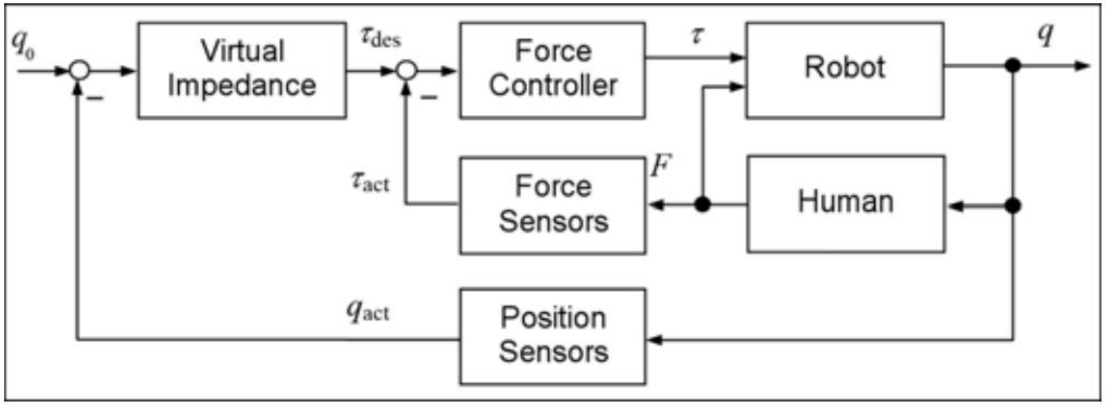
$$P_{i+1} = P_i + g e_i$$

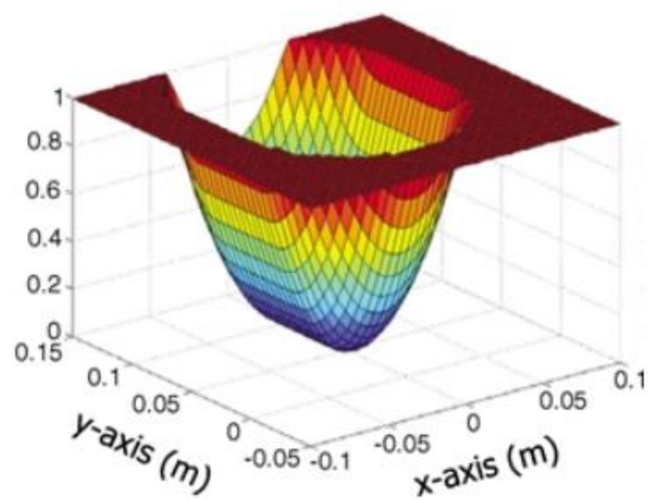
P	is the control parameter that is adapted (e.g. the movement timing, the gain of robot assistance force, etc.)
e_i	is the performance error (ability to initiate a movement, trajectory error, etc.)
g	is the gain factor

With this approach, the amount of assistance of the robot is related to the actual dexterity of the subjects: for example, the stiffness of the robot, that limits the patient's movement away from the desired path, increases if the trajectory error increases, and vice versa.

Controller: Performance-based adaptation 2/7

From the concept to the implementation for a 2D reaching task





$$F_{c,x} = -kx - b\dot{x}$$

$$F_{c,y} = \left\{ \begin{array}{c|c} -k_{bw}(y - y_{m.j.}) - b\dot{y} & y < y_{m.j.} \\ 0 & y_{m.j.} \le y \le l_m \\ -k(y - l_m) - b\dot{y} & y > l_m \end{array} \right\}$$

Potential energy of the controller for performance-based impedance controller, during a movement parallel to the y axis

Krebs et al, (2003), *Autonomous Robots*, 15(1), 7-20

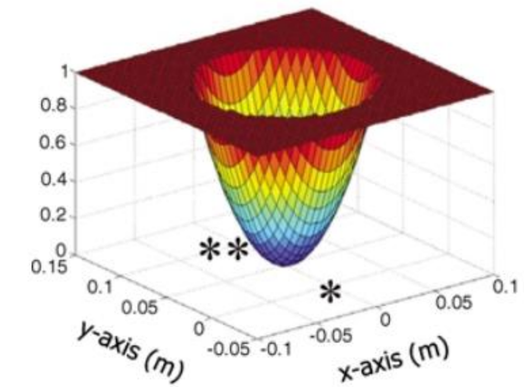
Controller: Performance-based adaptation 3/7

From the concept to the implementation for a 2D reaching task

Before

The force field of the robot was a *moving point*.

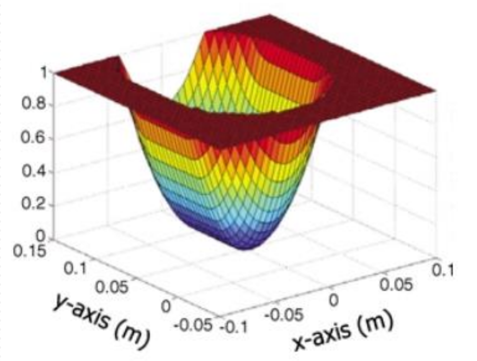
This means that the trajectory was completely defined by the robot, that moved the patient's hand from a starting point to a target, while the patient could only moves around the moving point.



After

The force field of the robot is a *moving box*.

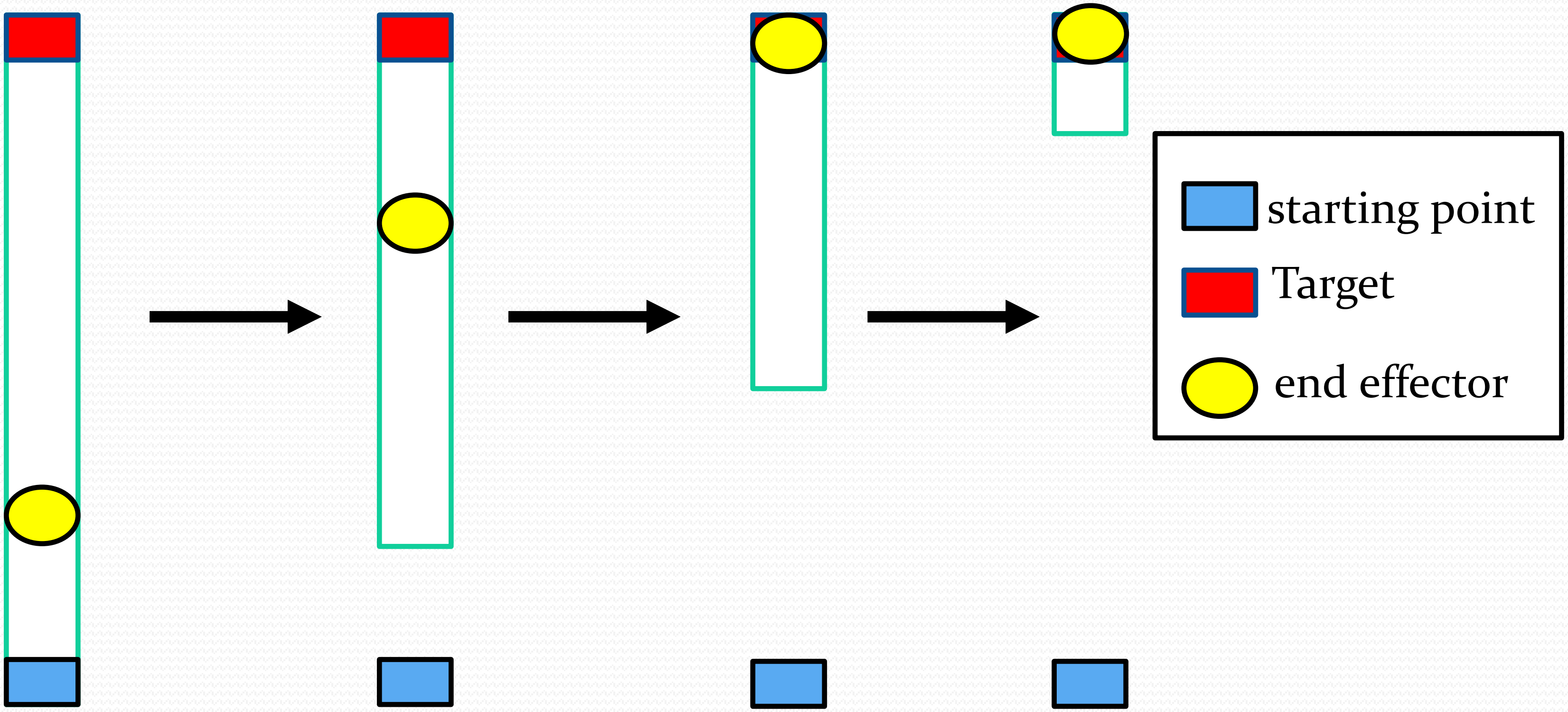
The force field can be thought of as a rectangular box. Inside the box, the patient can move freely (no force are applied) from the back wall (starting point) to the front wall (target). If patient is not able to reach the target, the back wall starts to move, pushing the end-effector toward the target.



Krebs et al, (2003), *Autonomous Robots*, 15(1), 7-20

Controller: Performance-based adaptation 4/7

From the concept to the implementation for a 2D reaching task

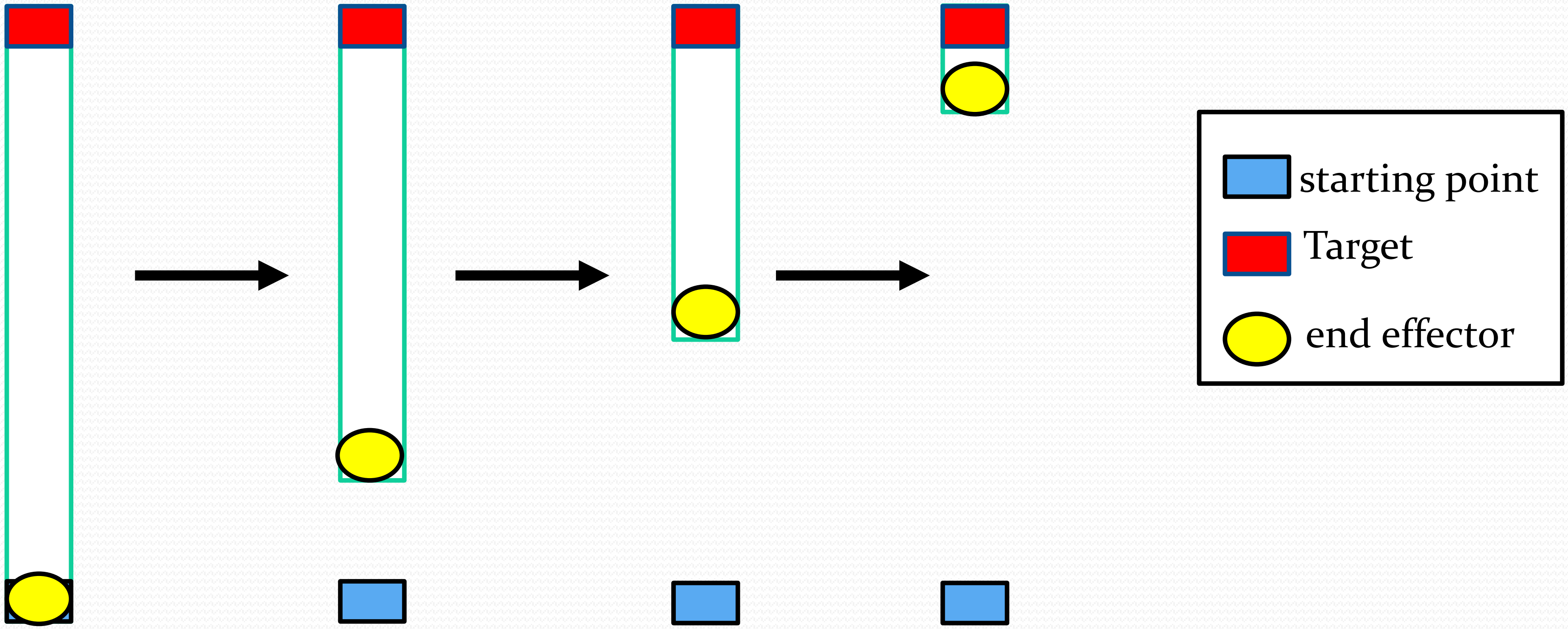


Patient can move freely inside the green box (no force field inside). In this case, he/she can reach the target without assistance (however, a lateral guide is always present).

Krebs et al, (2003), *Autonomous Robots*, 15(1), 7-20

Controller: Performance-based adaptation 5/7

From the concept to the implementation for a 2D reaching task



If the patient cannot reach the target, the back wall push the end-effector toward it.

Krebs et al, (2003), *Autonomous Robots*, *15*(1), 7-20

Controller: Performance-based adaptation 6/7

From the concept to the implementation for a 2D reaching task

Looking at the equations:

- While the stiffness of the previous controller tends to impede the patient from moving ahead of the desired trajectory, this controller allows capable patients to reach the target unassisted because $F_{c,y} = 0$ in the range $y_{m.\,j.} \leq y \leq l_m$.

Please notice:

- l_m is the distance from the starting point to the target (initial length of the box);
- y_{mj} is the current position of the moving (with a minimum jerk trajectory) back wall.

…

Krebs et al, (2003), *Autonomous Robots*, 15(1), 7-20

Controller: Performance-based adaptation 6/7

From the concept to the implementation for a 2D reaching task

…

The time allotted for the patient to make the move, t_m, and the primary stiffness of the impedance controller, k, are varied based on the patient's performance and variability, but the "back wall" stiffness, k_{bw}, is held constant.

By using a performance-based, progressive algorithm the therapy continuously challenges the patient.

Krebs et al, (2003), *Autonomous Robots*, *15*(1), 7-20

Controller: Performance-based adaptation 7/7

A modified version of the adaptive controller has been proposed:

$$P_{i+1} = fP_i + ge_i$$

P	is the control parameter that is adapted
e_i	is the performance error
f	is the **forgetting term**
g	is the gain factor

With standard adaptive controller (f=1) it was found that patients tended to allow the controller to take over, reducing their own effort. In other words, if patient do not move, $e_i \rightarrow 0$, P $\rightarrow$ constant and the patient is not more challenged.

This problem was addressed by modifying the standard adaptive controller to include a forgetting term that continuously attempts to reduce the assistance forces from the robot. Essentially, the resulting controller models the forces needed to assist the patient, as learned from tracking errors, but, at same time, try to reduce the assistance if the error tend to zero.

In this way, the **amount of assistance is at the same time augmented when the error increase**, and **reduced with time**.

RME: Robot Mediated Evaluation? Why?

In addition to delivering high-intensity, reproducible sensorimotor therapy, robotic devices are precise and reliable "measuring" tools that can be expanded with multiple sensors to record simultaneously kinematic and force data.

These measurements are objective and repeatable and can be used to provide patients and therapists with immediate measures of motor performance.

Reducing the time to evaluate improvement or deterioration may offer new opportunities for designing therapeutic programs and ultimately for increasing the efficiency of patients' care.

C. Bosecker et al. Kinematic robot-based evaluation scales and clinical counterparts to measure upper limb motor performance in patients with chronic stroke Neurorehab Neural Re (2010) 24.1: 62-69.

RME: Advantages?

Some of the advantages of **Robot Mediated Evaluation RME** are:

- It is more sensitive than conventional assessments that use an ordinal scale to quantify movement ability.
- It can help us gain a better understanding of the robot-aided therapy process, and thus can be used to tailor/optimize robotic therapy depending on a patient's condition.
- Can be used as:
  - '**Knowledge-of-Performance**' (KP) and
  - '**Knowledge-of-Results**' (KR),

  which can provide useful biofeedback variables that can improve motor recovery.

S. Balasubramanian et al. Robot-measured performance metrics in stroke rehabilitation Complex Medical Engineering, 2009. CME. ICME International Conference on. IEEE, 2009.

RME: Advantages?

- **Knowledge of performance** is information about the kinematics of the movement, and
- **knowledge of results** is information about the outcome of the movement

which have been shown to improve performance and skill in patients (e.g. children with CP).

D.E. Thorpe, J. Valvano The effects of knowledge of performance and cognitive strategies on motor skill learning in children with cerebral palsy. Pediatric Physical Therapy. (2002) 14.1: 2–15

R.T. Harbourne Accuracy of movement speed and error detection skills in adolescents with cerebral palsy. Percept Mot Skills (2001) 93: 419–431.

RME: Examples?

RUPERT I and II are powered by four pneumatic muscles to assist movement at the shoulder, elbow and wrist. The design was based on a kinematics model of the arm, which showed where to locate the pneumatic muscles and how much force was needed for normal reaching and feeding movements. The mechanical arm is adjustable to accommodate different arm lengths and body sizes.

RME: Examples?

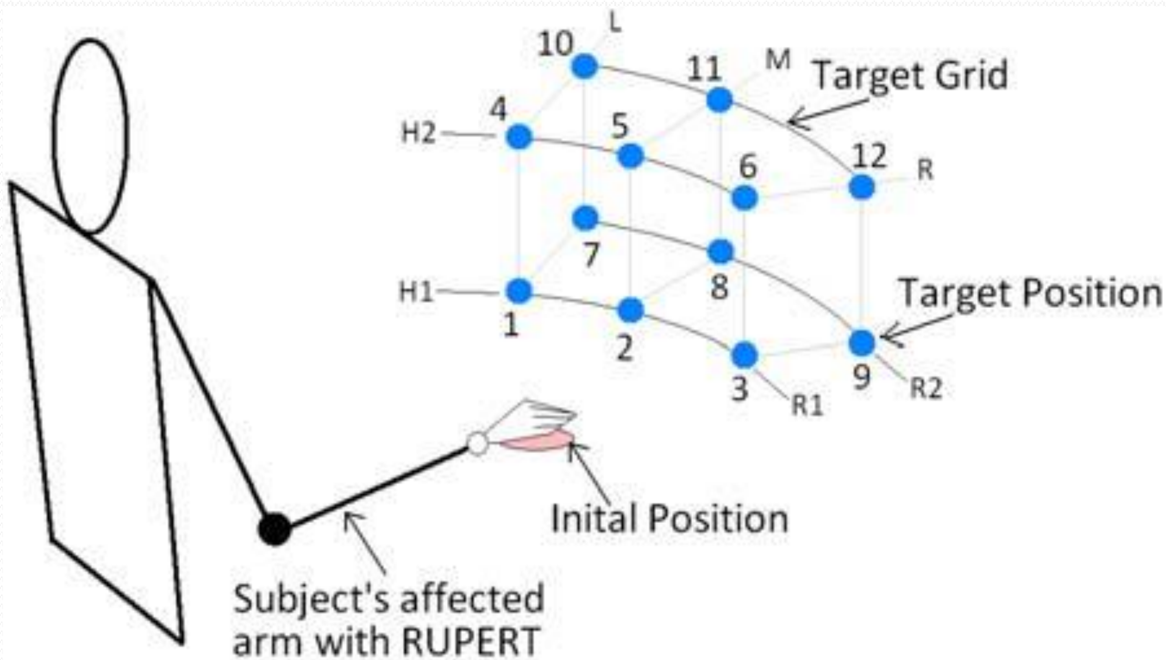
Recent research suggests that stroke survivors can recover significant use of their arms by performing repetitive motor function exercises over a period of time.

This labor-intensive physical therapy is expensive, however, claiming up to 4 percent of the national health budget, according to the National Institutes of Health.

Moreover, health insurers may limit or deny coverage before stroke survivors achieve best results.

The availability of a device like RUPERT, that could be used at home with greater frequency and for a longer period of time, may prove to be a more cost-effective approach that would provide better results.

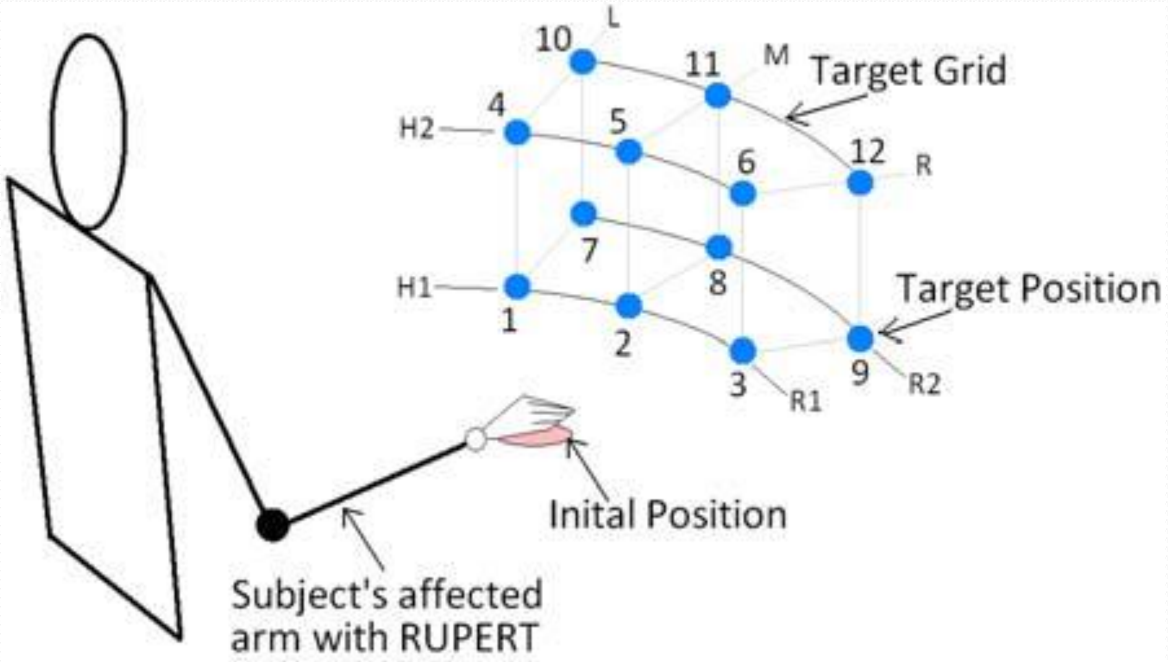
RME: Examples?



RUPERT can be used for training simple point-to-point reaching movements in a 3D workspace with gravity. The therapy protocol used for RUPERT-aided therapy consists of patient's moving to different targets located in a workspace of the robot.

The targets (blue balls in Figure) are arranged in a target grid, that includes two reaching distances (R1 and R2), two reaching heights (H1 and H2), and three movement directions (Left, Middle and Right), which results in a total of twelve targets.

RME: Advantages?



RUPERT is instrumented with two types of sensors, namely:

- **joint angle sensors**: can be used for calculating various performance metrics related to the movement kinematics
- and **pressure sensors**: can be used for estimating gross performance metrics related to movement kinetics.

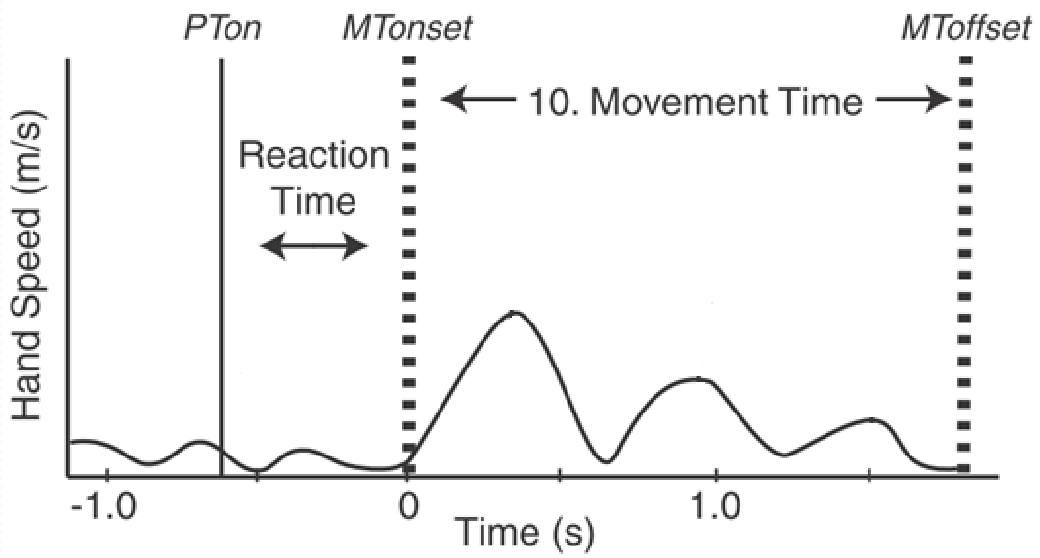
RME: Indices? How many? For what?

Robotic indices for the evaluation of upper limb performance could be summarized as follows:

1. Movement time;
2. Movement smoothness;
3. Movement speed;
4. Trajectory error;
5. Synergy between joint;
6. Force applied by the subject.

O. Celik et al. Normalized movement quality measures for therapeutic robots strongly correlate with clinical motor impairment measures. IEEE Trans. Neural Syst. Rehabil. Eng. 18.4 (2010): 433-444.

RME: Movement time?



1. **Movement Time (s)**: the time between movement **onset** and **offset**, typically identified with the use of a single velocity threshold (e.g. 5 mm/s or 5% peak velocity).

2. **Reaction time (s)**: is the time between illumination of the target and onset of movement.

Both indices are expected to decrease with practice.

A.M. Coderre et al. "Assessment of upper-limb sensorimotor function of subacute stroke patients using visually guided reaching." Neurorehab Neural Re 24.6 (2010): 528-541.

RME: Movement smoothness?

Smoothness is widely regarded as a hallmark of skilled, coordinated movement. Jerk, the time derivative of acceleration, has been used as an empirical measure of this quality. Different metrics has been proposed, but it was showed that a dimensionless jerk-based measure

1. **(Normalized Jerk)** properly quantifies common deviation from smooth, coordinated movement.

$$NJ = \sqrt{\frac{1}{2}\frac{T^5}{L^2}\int_{t_i}^{t_f} \dddot{x}(t)^2\,dt}$$

Where:

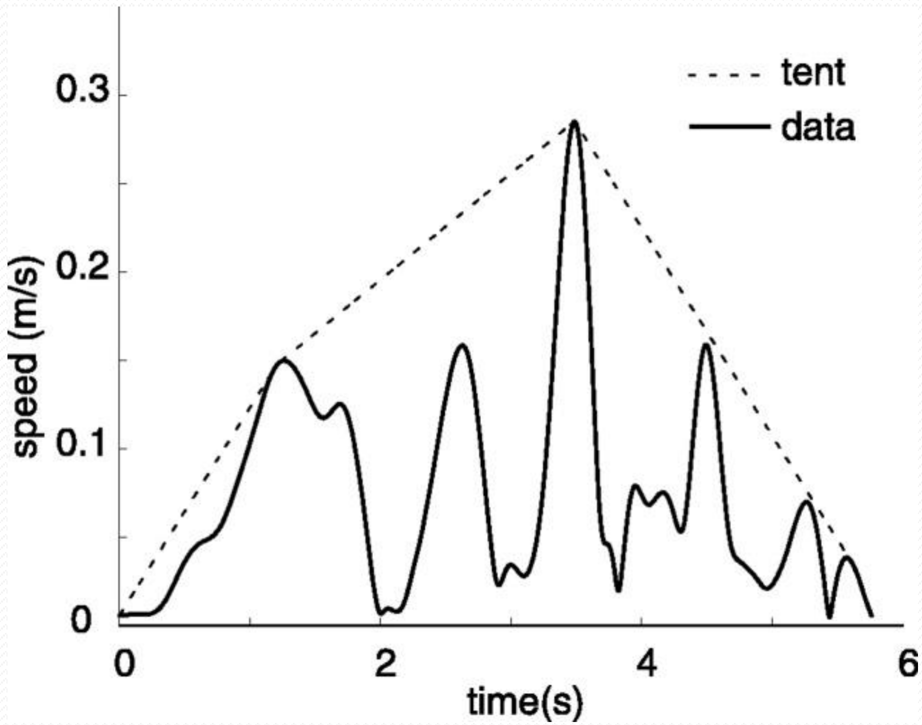
- T is the duration of the movement,
- L is the length of the movement, and
- x(t) is the trajectory of the movement

It is expected to reduce with recovery.

Hogan, Neville, and Dagmar Sternad. "Sensitivity of smoothness measures to movement duration, amplitude, and arrests." Journal of motor behavior 41.6 (2009): 529-534.

RME: Movement smoothness?

2. **Speed metric**: is the normalized mean speed (i.e., the mean of the speed divided by the peak speed).
3. **Mean arrest period ratio**: is the portion of time that movement speed exceeds a given percentage of peak speed.
4. **Peaks metric:** is the number of peaks in a speed profile.
5. **Tent metric**: is the ratio of the area under the speed curve to the area under a curve “stretched” over the top of it.



Rohrer, Brandon, et al. "Movement smoothness changes during stroke recovery." The Journal of Neuroscience 22.18 (2002): 8297-8304.

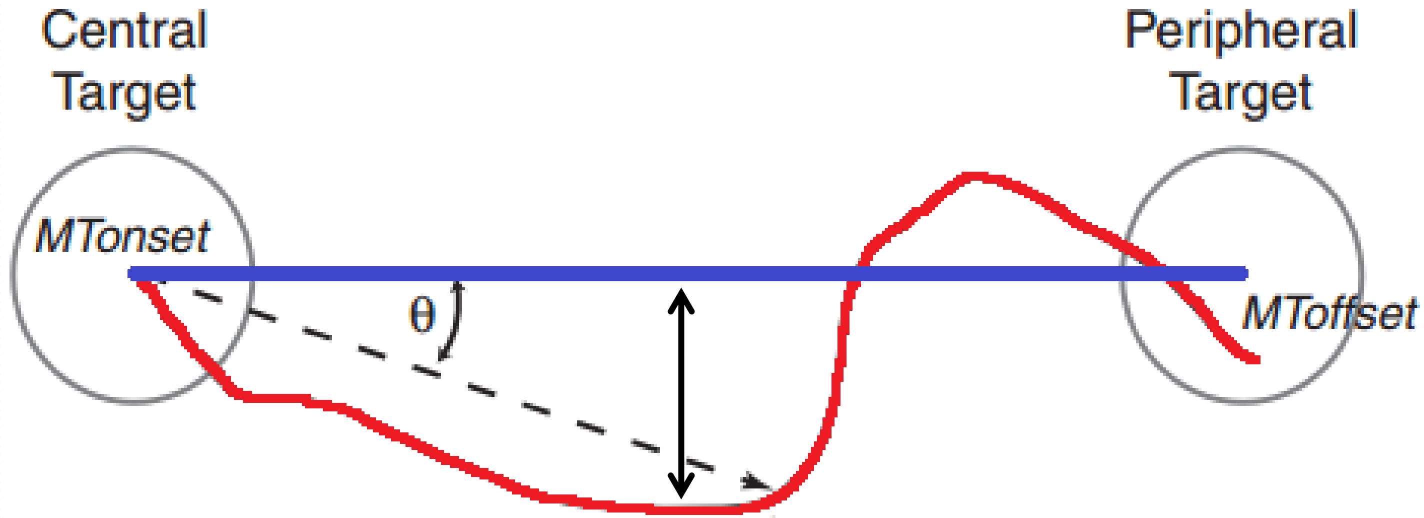
RME: Movement speed?

1. **Mean speed**: is the mean value of patient velocity. It is expected to increase with recovery
2. **Peak speed**: is the peak value of patient velocity. It is expected to increase or decrease depending on the required goal (velocity vs. smoothness).

Zollo, L., et al. "Robotic technologies and rehabilitation: new tools for upper-limb therapy and assessment in chronic stroke." European journal of physical and rehabilitation medicine 47.2 (2011): 223-236.

Zollo, L., et al. "Quantitative evaluation of upper-limb motor control in robot-aided rehabilitation." Medical & biological engineering & computing 49.10 (2011): 1131-1144.

RME: Trajectory error?



1. **Aiming angle (AA)**: it is defined as the angular difference between target direction and the direction of travel from the starting point up to peak speed point. The angular displacement is expected to reduce with the therapy.
2. **Length ratio (LR)** or **Trajectory Error (TE)** : it is defined as the length ratio between the actual patient curve and the desired straight line. It is expected to decrease with practice.
3. **Lateral deviation (LD)**: it is defined as the deviation from the straight line that connects the initial position to the target, evaluated at the time of peak velocity, or at its maximum value.

RME: Synergy between joint 1/7?

The redundancies in upper limb joints enable the production of different strategies to complete a task.

Motor synergies are presented as a potential strategy used by the CNS to simplify the computational burden of coordinating the many degrees of freedom of the musculoskeletal system to achieve a variety of behavioral goals.

In persons with stroke, **abnormal synergies** are a sign of persistent neurological deficit and result in loss of independent joint control, which disrupts the kinematics of voluntary movements. Synergies are thus are considered a form of impairment and the ability to "extinguish" synergistic movements is regarded as a goal of therapy.

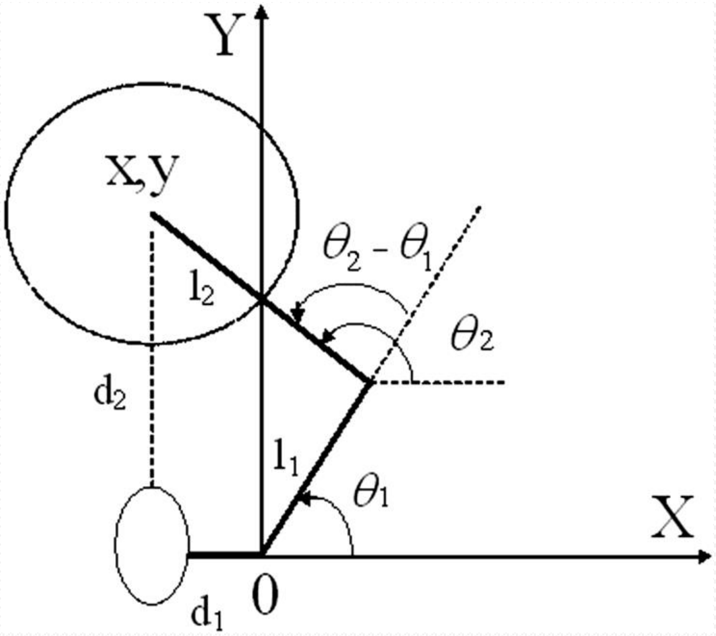
To put it in a nutshell, impaired subjects reduce the number of degrees of freedom of the upper limb, "moving together", i.e. with the same motor pattern, the shoulder and the elbow joints.

Dipietro, L., et al. "Changing motor synergies in chronic stroke." Journal of neurophysiology 98.2 (2007): 757-768.

RME: Synergy between joint 2/7?

The circle-drawing task involve the coordination of both shoulder and elbow, thus it is a complex task for impaired subjects.

To quantify the independence of the subject's shoulder and elbow joint movements a 2D model of the upper limb performing a circle drawing task has been used. This model allows to obtain the shoulder angle (θ_1) and the elbow angle ($\theta_2 - \theta_1$), given the position of the end-effector in the workspace (x,y) and the anthropometric measures of the subject (l_1 and l_2).

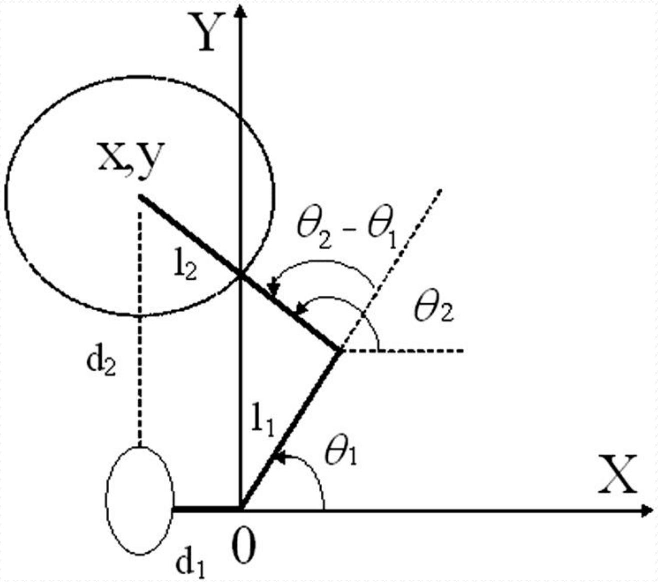


Dipietro, L., et al. "Changing motor synergies in chronic stroke." Journal of neurophysiology 98.2 (2007): 757-768.

RME: Synergy between joint 3/7?

Starting from the computed angles, the following index can be obtained:

$$\mathrm{JACM} = \frac{\mathbf{C}(\boldsymbol{\theta}_1, \boldsymbol{\theta}_2)}{\sqrt{\mathbf{C}(\boldsymbol{\theta}_1, \boldsymbol{\theta}_1) \cdot \mathbf{C}(\boldsymbol{\theta}_2, \boldsymbol{\theta}_2)}}$$



Where:

C is the covariance matrix,

θ_1 the shoulder angle and

θ_2 the elbow angle.

See the matlab function *corrcoeff*!

Dipietro, L., et al. "Changing motor synergies in chronic stroke." Journal of neurophysiology 98.2 (2007): 757-768.

RME: Synergy between joint 4/7?

$$\text{JACM} = \frac{\mathbf{C}(\boldsymbol{\theta}_1, \boldsymbol{\theta}_2)}{\sqrt{\mathbf{C}(\boldsymbol{\theta}_1, \boldsymbol{\theta}_1) \cdot \mathbf{C}(\boldsymbol{\theta}_2, \boldsymbol{\theta}_2)}} = \begin{bmatrix} 1 & r_{\vartheta_2 \vartheta_1} \\ r_{\vartheta_1 \vartheta_2} & 1 \end{bmatrix}$$

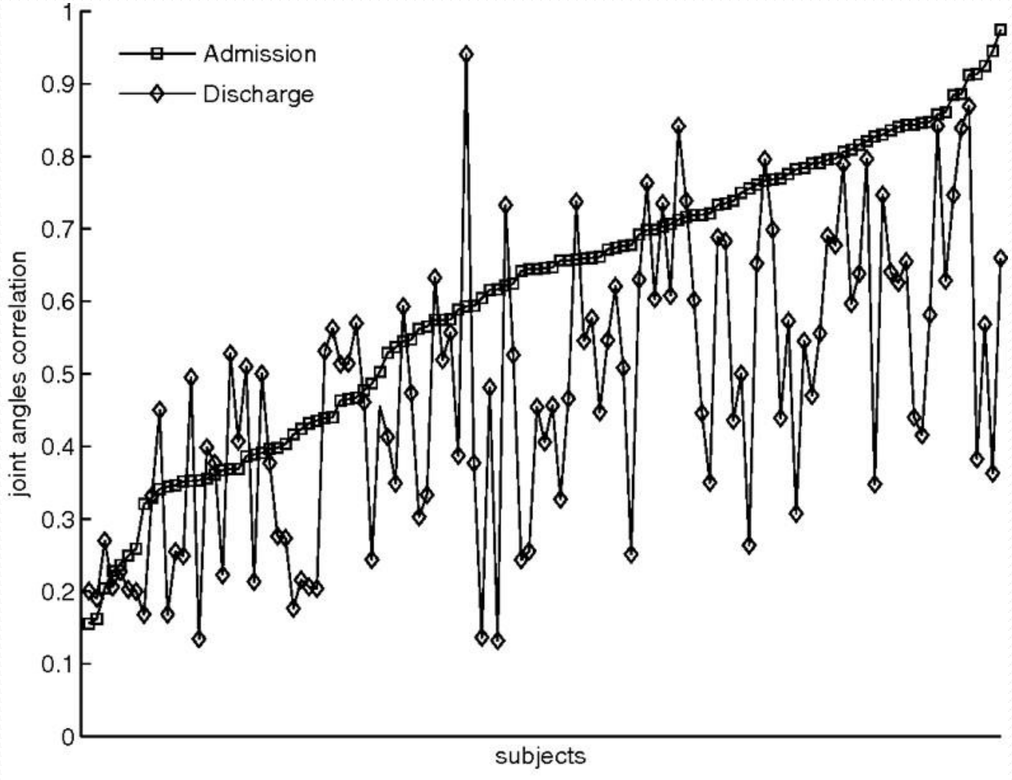
That is the matrix of correlation coefficients, that is related to the covariance matrix as showed.
It is a simmetric matrix; *r* is the correlation coefficient between θ1 and θ2 and is the value used to quantify the synergy between the two joints.

Its value range from 0 (no correlation at all) to 1 (same pattern).

Dipietro, L., et al. "Changing motor synergies in chronic stroke." Journal of neurophysiology 98.2 (2007): 757-768.

RME: Synergy between joint 5/7?

Joint angles correlation values for admission and discharge for each subject.

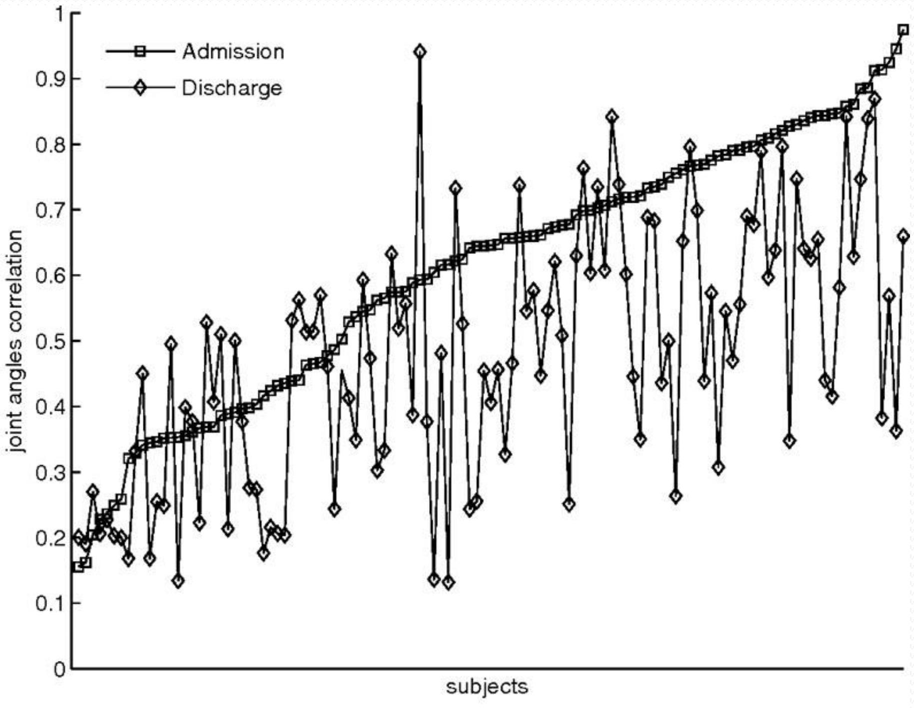


After robotic treatment, almost all subjects (especially those with higher values of JACM) reduced their motor synergies.

Dipietro, L., et al. "Changing motor synergies in chronic stroke." Journal of neurophysiology 98.2 (2007): 757-768.

RME: Synergy between joint 6/7?

Joint angles correlation values (y axis) for admission and discharge, for each subject (x axis).



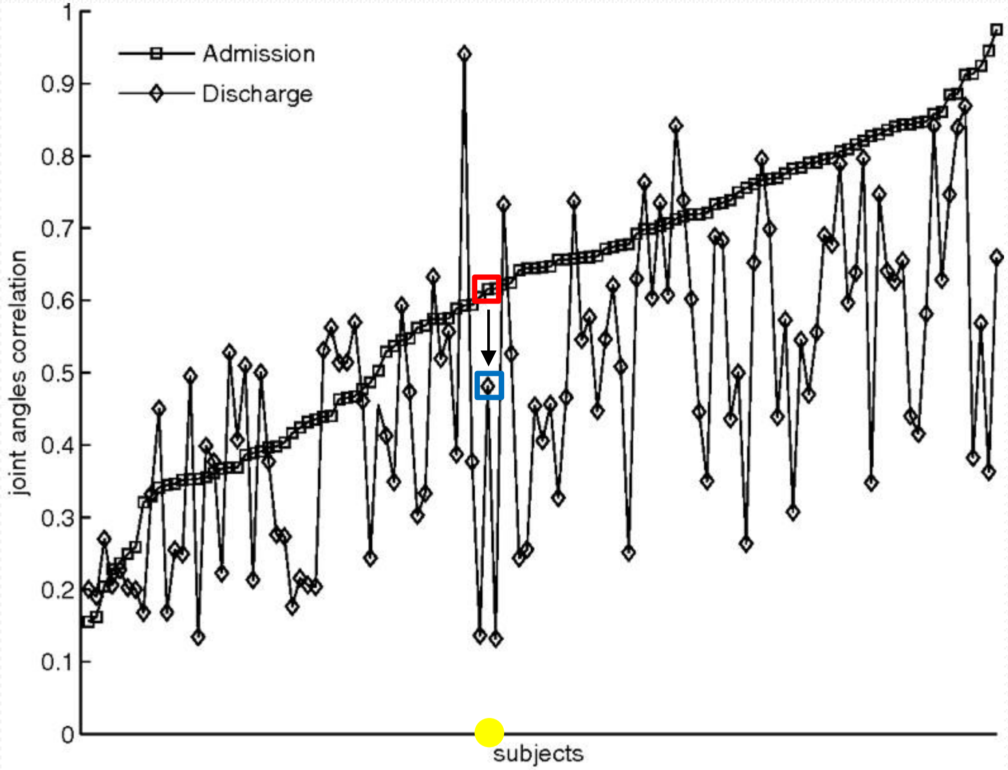
For each patient, two values of JACM are reported (at the admission and after robotic treatment).

Subjects are sorted according to the initial value of JACM
(the increasing curve in the graph).
Points around the curve represent the JACM values for each subject after robotic treatment.

Dipietro, L., et al. "Changing motor synergies in chronic stroke." Journal of neurophysiology 98.2 (2007): 757-768.

RME: Synergy between joint 7/7?

Joint angles correlation values (y axis) for admission and discharge, for each subject (x axis).



As example, in the figure the value of JACM of a single subject (yellow circle) are highlighted : admission (red) and after robotic treatment (blue)

After robotic treatment, almost all subjects (especially those with higher values of JACM, then presenting higher abnormal motor synergies) reduced their motor synergies.

Dipietro, L., et al. "Changing motor synergies in chronic stroke." Journal of neurophysiology 98.2 (2007): 757-768.

RME: Force applied by the subject?

1. **Mean force**: is the mean value of the force exerted by the patient during motion.
2. **Peak force**: is the peak value of the force exerted by the patient during motion.

The previous indices are expected to reduce with training in free motion, and to increase in resistive motion.

3. **Useful force**: it measures the amount of mean force directed towards the target, and it is calculated by weighting the mean force value with the aiming angle.
4. **Useful peak force**: it measures the amount of peak force directed towards the target, and it is calculated by weighting the mean force value with the aiming angle.

The previous indices are expected to increase with recovery.

Zollo, L., et al. "Robotic technologies and rehabilitation: new tools for upper-limb therapy and assessment in chronic stroke." Eur J Phys Rehabil Med (2011) 47.2: 223-236.

RME: Performance-based robot therapy?

There is no reason to believe that a "one-size-fits-all" optimal treatment exists. Instead therapy should be tailored to each patient's needs and abilities.

One innovative modality of robotic therapy is the inclusion of specific, movement-related feedback and control parameter specification via a performance-based progressive algorithm.

By using a performance-based, progressive algorithm, the therapy continuously challenges the patient.

Krebs, Hermano Igo, et al. "Rehabilitation robotics: Performance-based progressive robot-assisted therapy." Autonomous Robots 15.1 (2003): 7-20.

RME: Performance-based robot therapy?

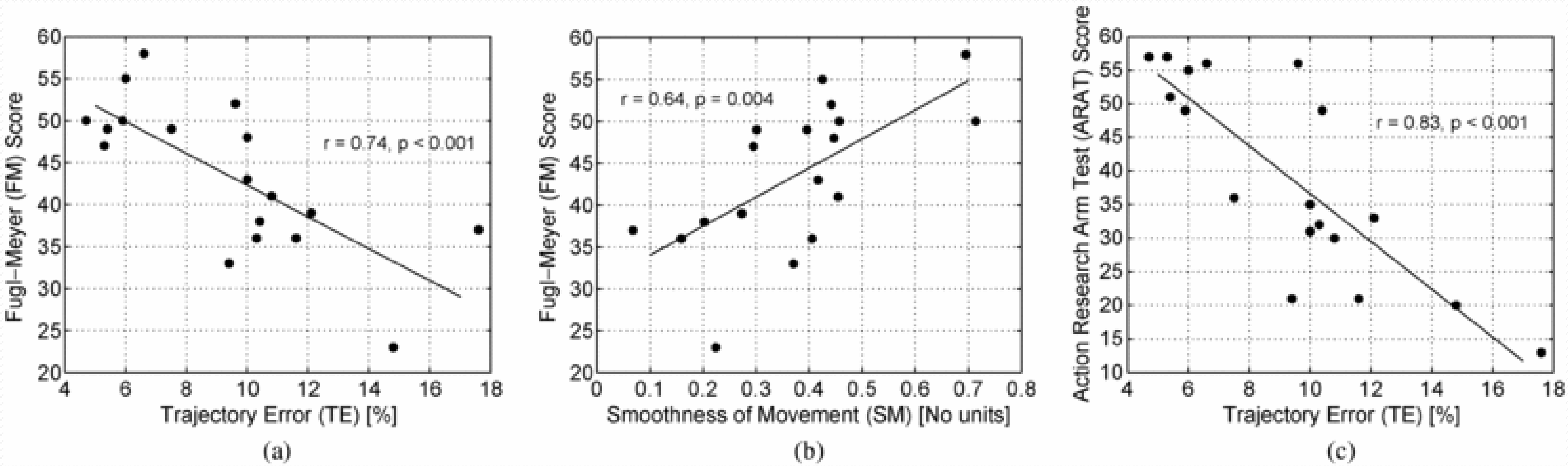
Title of Assessment	Fugl-Meyer Assessment of Motor Recovery after Stroke
Purpose	• Evaluates and measures recovery in post-stroke hemiplegic patients • Used in both clinical and research settings • One of the most widely used quantitative measures of motor impairment (Gladstone et al, 2002)
Description	• Items are scored on a 3-point ordinal scale • 0 = *cannot perform* • 1 = *performs partially* • 2 = *performs fully* • Maximum Score = 226 points • The Five domains assessed include: • Motor function (UE maximum score = 66; LE maximum score = 34) • Sensory function (maximum score = 24) • Balance (maximum score = 14) • Joint range of motion (maximum score = 44) • Joint pain (maximum score = 44) • Subscales can be administered without the using the full test • Modified (abbreviated) versions have been developed (Hsueh et al, 2008)
…	

RME: Performance-based robot therapy?

...	
Area of Assessment	Activities of Daily Living; Functional Mobility; Pain
Body Part	Not Applicable
ICF Domain	Body Function
Domain	Motor; Sensory
Assessment Type	Observer
Length of Test	06 to 30 Minutes
Time to Administer	30 minutes (shortened versions $\geq$ 10 minutes)
Number of Items	226 items across 5 domains
Equipment Required	The FMA Motor Test requires: • Tennis ball • A small spherical shaped container • A tool to administer reflex tests • Enough space is needed for a patient to move around freely • If possible, space should be a quiet, private room with few distractions
Training Required	Review of manual

RME: Is it correlated with clinical scale?

In the literature, contrasting result have been reported.

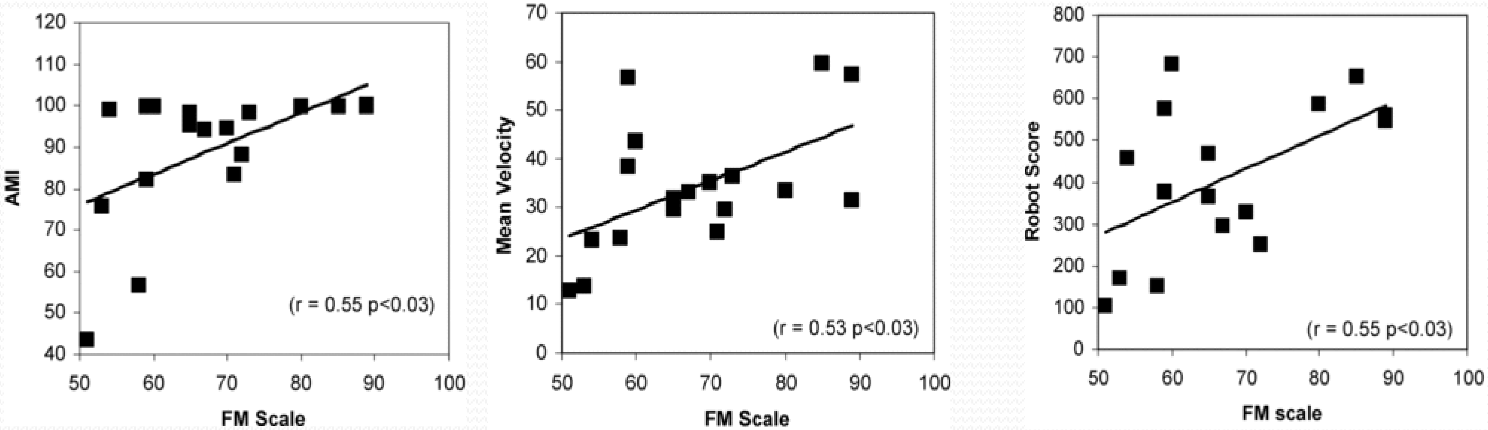


(a) **Strong and significant correlation** exists between FM and TE measures.
(b) **Moderate and significant correlation** between FM and SM measures.
(c) **Very strong and significant correlation** between ARAT and TE measures.

O. Celik et al. Normalized movement quality measures for therapeutic robots strongly correlate with clinical motor impairment measures. IEEE Trans. Neural Syst. Rehabil. Eng. 18.4 (2010): 433-444.

RME: Is it correlated with clinical scale 1/2?

In the literature, contrasting result have been reported.

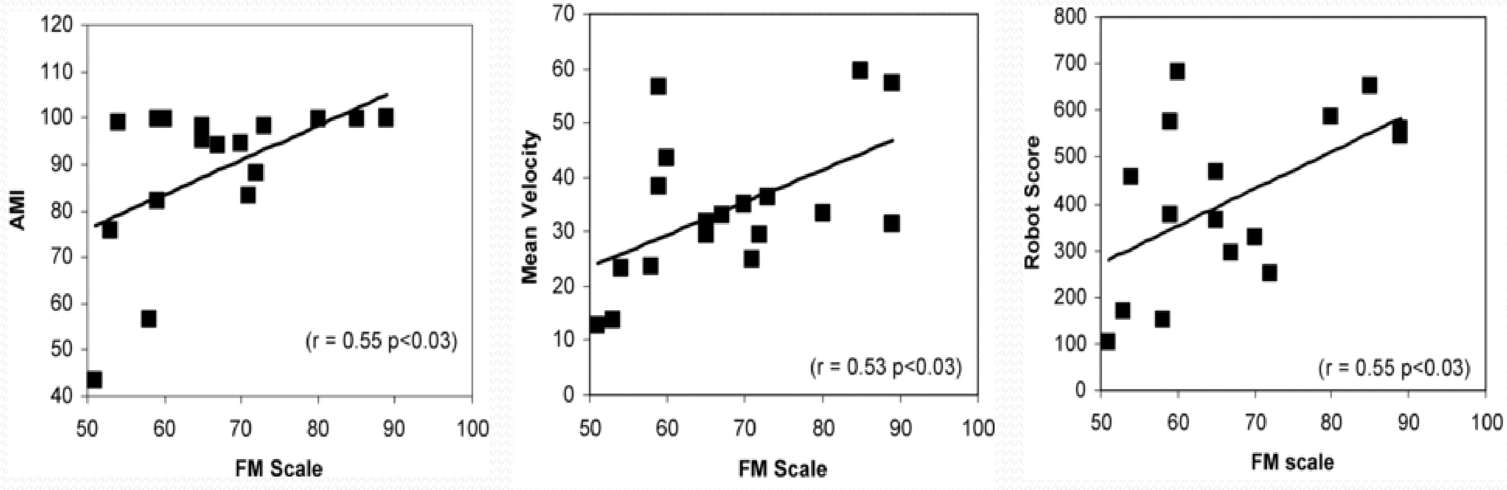


Robot score (RS) = obtained by dividing into ten segments the path between the starting point and the target. The score increased for each segment covered by means of the patient's active movement.
AMI = RS/TS*100, where TS is the theoretical score (all the movements performed by the subject without robot assistance)

R. Colombo et al. "Robotic techniques for upper limb evaluation and rehabilitation of stroke patients." Neural Systems and Rehabilitation Engineering, IEEE Transactions on 13.3 (2005): 311-324.

RME: Is it correlated with clinical scale 2/2?

In the literature, contrasting result have been reported.



"*We obtained:*

- *a moderate significant correlation coefficient for all three robot measured parameters and the FM scale and*
- *a weaker, non significant correlation for the MP and MSS variables*".

R. Colombo et al. "Robotic techniques for upper limb evaluation and rehabilitation of stroke patients." Neural Systems and Rehabilitation Engineering, IEEE Transactions on 13.3 (2005): 311-324.

1. Introduction on robot mediated therapy

2. Rehabilitation robotic systems

3. Effectiveness

4. Robot mediated therapy @SAPIENZA

Effectiveness: Approach?

1. Control the subject against themselves:
   - to submit half the subjects to a condition where they receive robot treatment, along with any other treatments, in the first phase followed by a second phase where only the other treatments continue.
   - The second group has this order reversed.
2. Randomized control trial (RCT) subjects are divided into:
   - a treatment and
   - a control group

in the case of robots for Neurorehabilitation, is costly.

W.S. Harwin et al. Assessing the effectiveness of robot facilitated neurorehabilitation for relearning motor skills following a stroke Med Biol Eng Comput (2011) 49:1093–1102

Effectiveness: Expected results?

- Movements tend to become faster with the robot mediated therapy?
- Movements become more stable?
- Movements get smoother, exhibiting less oscillations or putative submotions as therapy progresses?
- Force directing ability improves?
- Amount of assistance provided by the robot decreases with therapy?

Balasubramanian et al. Am. J. Phys. Med. Rehabil. & Vol. 91, No. 11 (Suppl), 2012

Effectiveness: Outcomes of literature survey?

250 papers up to 2012 and articulated in:

- **Tipo I: 67 papers**

  The pilot consideration-of-concept study is often represented by small case series testing clinical feasibility and potential benefit for a new device;

- **Tipo II: 24 papers**

  The development-of-concept study would include

  - a standardized description of the intervention,
  - a control group (preferably using an active treatment),
  - randomization, and
  - blinded outcome assessments;

- …

Lo A.C.: Clinical designs of recent robot rehabilitation trials. Am J Phys Med Rehabil 2012;91(Suppl):204-216

Effectiveness: Outcomes of literature survey?

- **Tipo III & IV : 5 papers**

Demonstration-of-concept and proof-of-concept trials, which fall more along the lines of a Food and Drug Administration phase II/III multicentered clinical trial. These studies would have:

  - an active control group,
  - a well-defined intervention,
  - the use of an outcome powered to detect reliable change, and
  - ideally a measure that is clinically meaningful functionally and important to the patient.

Lo A.C.: Clinical designs of recent robot rehabilitation trials. Am J Phys Med Rehabil 2012;91(Suppl):204-216

Effectiveness: Outcomes of literature survey?

FINDINGS:

- few larger clinical trials;
- challenges of conducting rehabilitation trials in general;
- larger issues:
    - determining testable theories of rehabilitation,
    - choosing the study population most likely to respond,
    - selecting the appropriate control groups,
    - dosing the intervention, and then
    - choosing the appropriate outcomes responsive to the therapy.
- showing that a robot can be used feasibly in a clinical setting will not answer these unresolved questions.

Lo A.C.: Clinical designs of recent robot rehabilitation trials. Am J Phys Med Rehabil 2012;91(Suppl):204-216

Effectiveness: Outcomes of literature survey?

SUGGESTIONS:

- Clarify the acute/subacute/chronic categories.
- Use the same scales for outcome measure.
- Provide a clear description of the intervention.

Peter et al. Robot-mediated upper limb physiotherapy: review and recommendations for future clinical trials International Journal of Rehabilitation Research 2011, 34:196–202

Cochrane Review (Evidence based):

- Robot training for upper extremity: valid
- Robot training for lower extremity: unclear

1. Introduction on robot mediated therapy
2. Rehabilitation robotic systems
3. Effectiveness

4. Robot mediated therapy @SAPIENZA

Effectiveness: Pediatric robotic rehab?

- Pediatric rehabilitation focuses on maximizing the function and enhancing the lives of children with a wide range of conditions such as cerebral palsy, spina bifida, stroke, brain injury, genetic abnormalities and other developmental disabilities.
- Although, there are several publications about pediatric rehabilitation, few of them are about robotic rehab.

N. Garcia et al Trends in rehabilitation robotics Med Biol Eng Comput (2011) 49:1089–1091

- Children will likely be more engaged in robot-assisted therapies that are fun and interactive
- The potential of rehabilitation technologies to improve clinical practice and outcomes for children with CP and acquired brain injury is great.

Fasoli et al New Horizons for Robot-Assisted Therapy in Pediatrics American Journal of Physical Medicine & Rehabilitation (2012)

@SAPIENZA: Premise

Sustainable growth in the area of rehabilitation robotics will be achieved:

- with multi-disciplinary efforts,
- engineers must recognize the need to bring the technology out of the laboratory and into the clinic,
- only if we engage clinicians (physicians and therapists) and patients (and their families).

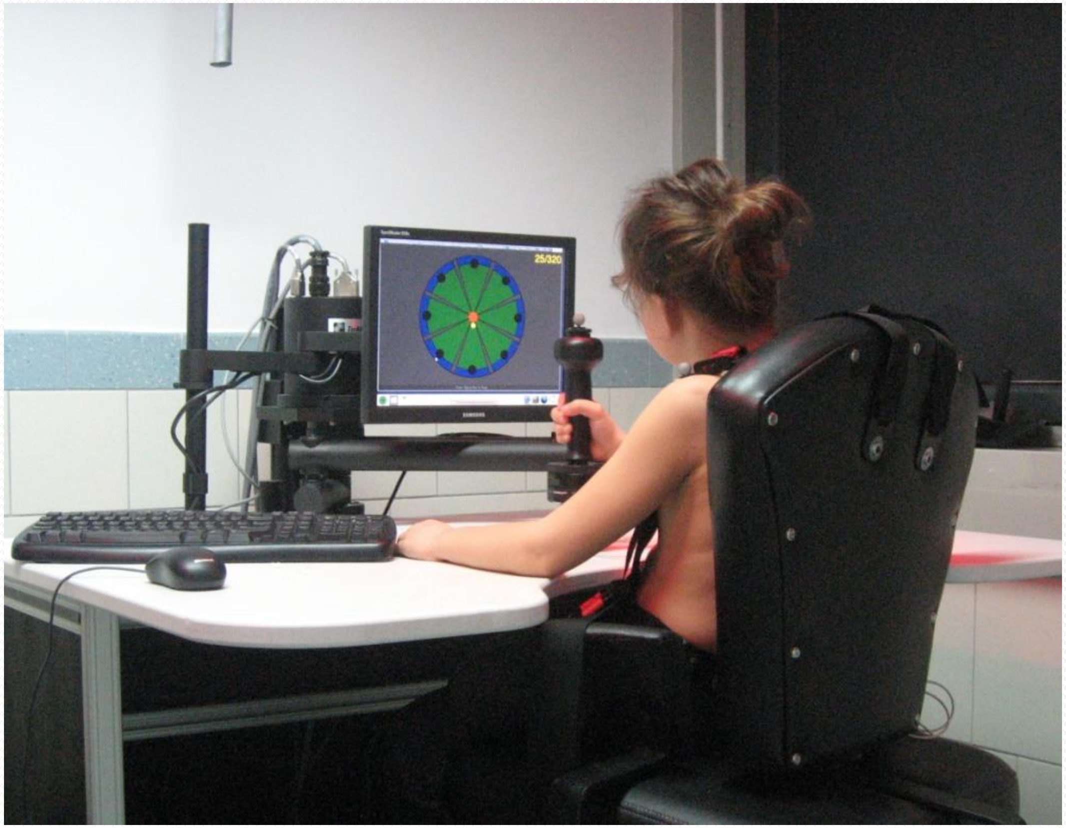
HI. Krebs et al Robot-assisted task-specific training in cerebral palsy Developmental Medicine & Child Neurology 2009, 51 (Suppl. 4): 140–145

Assistive strategies with InMotion Arm Robot

InMotion Arm Robot: The robotic system provides 2 translational degrees-of-freedom (DOFs) for shoulder and elbow joint movements.

Powered mode: motors help the subject to perform the required task (planar reaching movements).

Unpowered or “evaluative” mode: motors are turned off.



Assistive strategies with InMotion Arm Robot

The InMotion2 robotic system (Interactive Motion Technologies, Inc., Boston, MA, USA) allows subjects to execute reaching movements in the horizontal plane. During the movements the device can assist or resist the subject's movements. The machine was designed:

- to have a low intrinsic end-point impedance (i.e. be back-driveable),
- to have a low and nearly- isotropic inertia (1 ± 0.33 kg, maximum anisotropy 2:1) and friction (0.84 ± 0.28 N, maximum anisotropy 2:1),
- be capable of producing a predetermined range of forces (0–45 N) and impedances (0–2000 N/mm).

Assistive strategies with InMotion Arm Robot

- A monitor in front of the subject displays the exercises to be performed.
- A second monitor is dedicated to the operator.
- The workstation is mounted on a custom-made adjustable chair, which allows the chair to be rotated 360° and translated 0.5 m toward a table-top, specially designed to facilitate transfer of patients with wheelchair.
- …

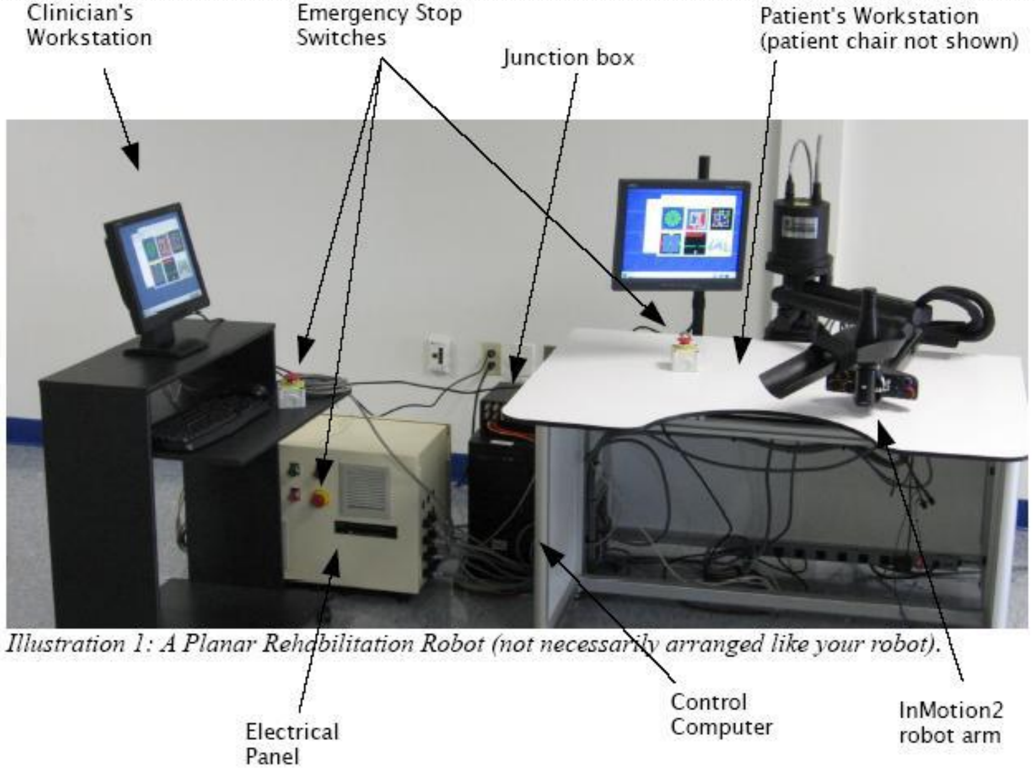


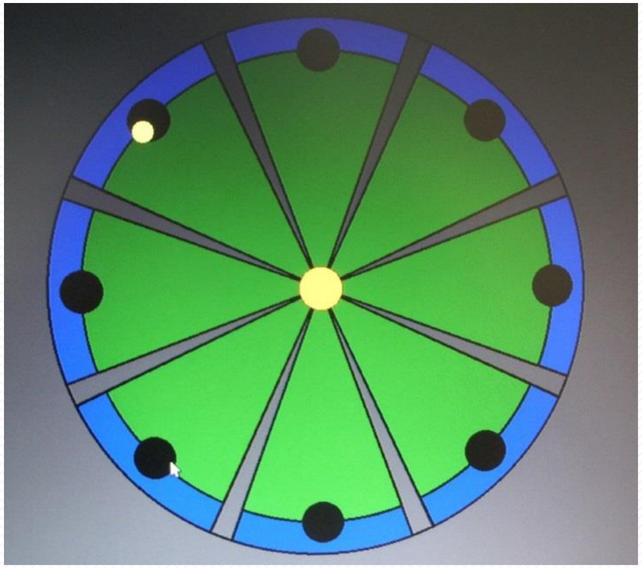
Illustration 1: A Planar Rehabilitation Robot (not necessarily arranged like your robot).

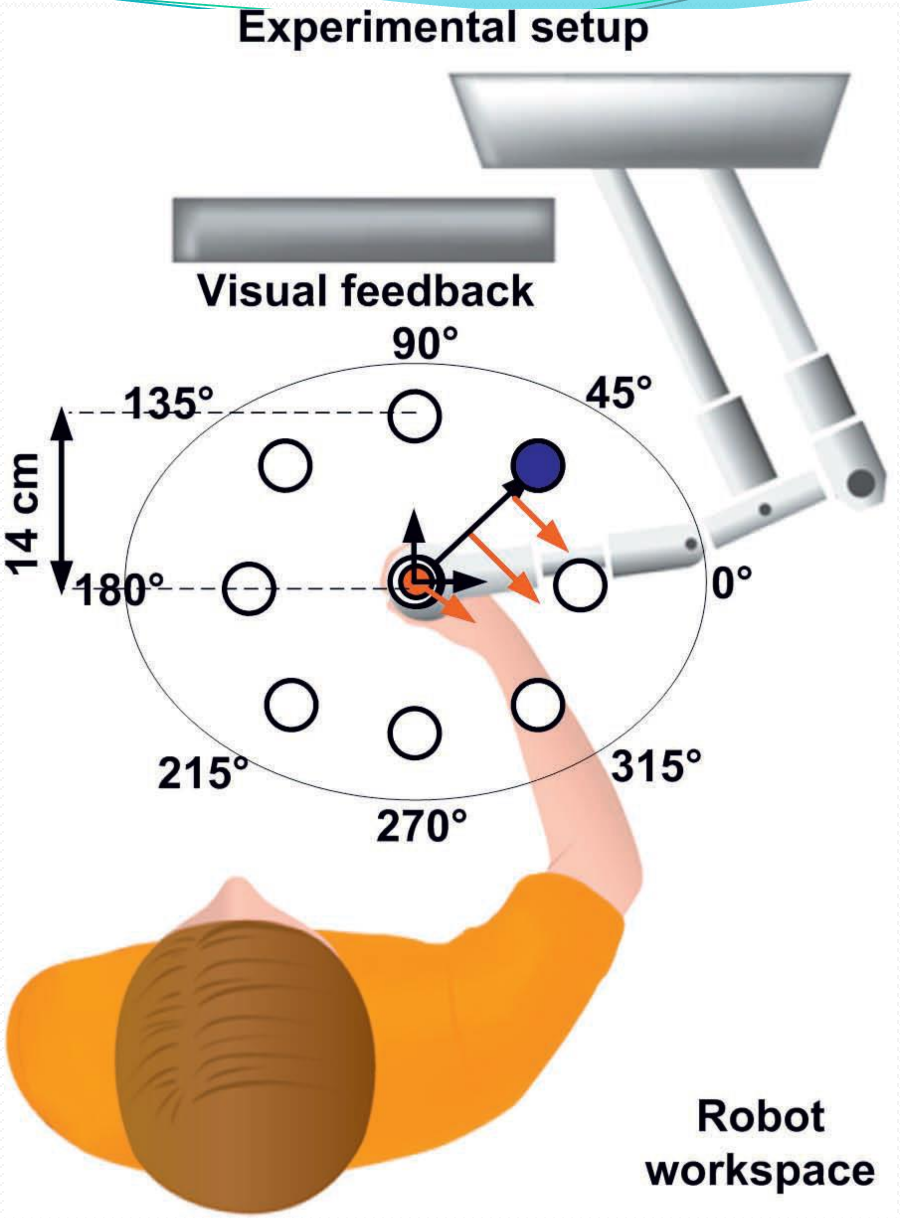
Assistive strategies with InMotion Arm Robot

- …
- The robot can move, guide, or perturb the movement of the upper limb of the subjects and can record end-effector kinematics and mechanical quantities such as the position, velocity, and applied forces.
- A 6 axis force/torque transducer is placed on the end-effector.
- The subject's arm was placed in a customized arm support attached to the end-effector of the robot arm.

Assistive strategies with InMotion Arm Robot

Each subject was asked to perform goal-directed, planar reaching tasks, which emphasized shoulder and elbow movements.





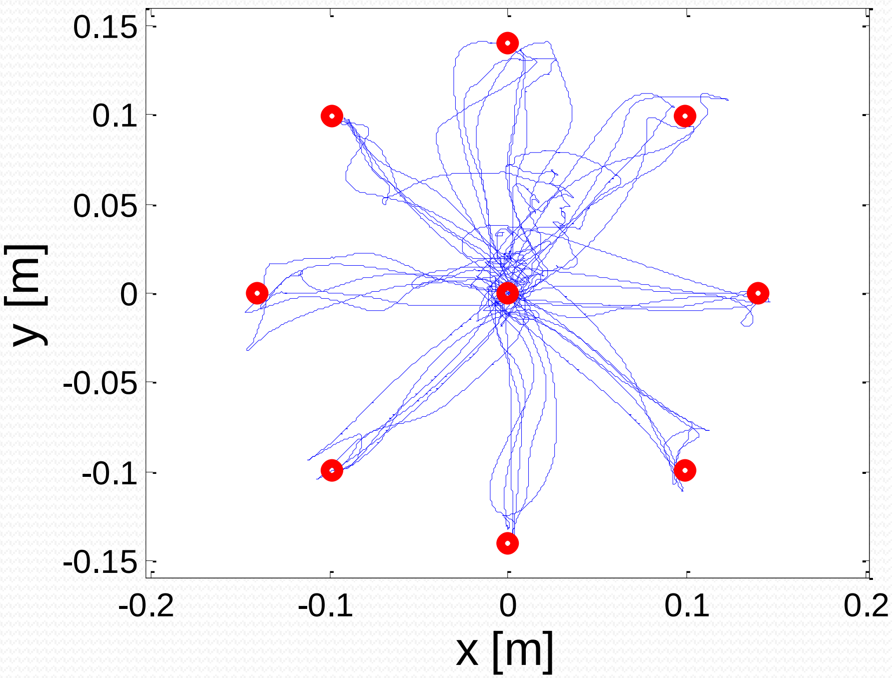
Assistive strategies with InMotion Arm Robot

As they attempted to move the robot's handle toward designated targets, the robot was able to recognize the active component of movement and allows the patient to perform the movements without assistance.
If the patient was unable to reach to the target, the robot supported the patient by driving the end-effector to the target.
The computer screen in front of the patient provided visual feedback of the target location and the movement of the robot end-effector.

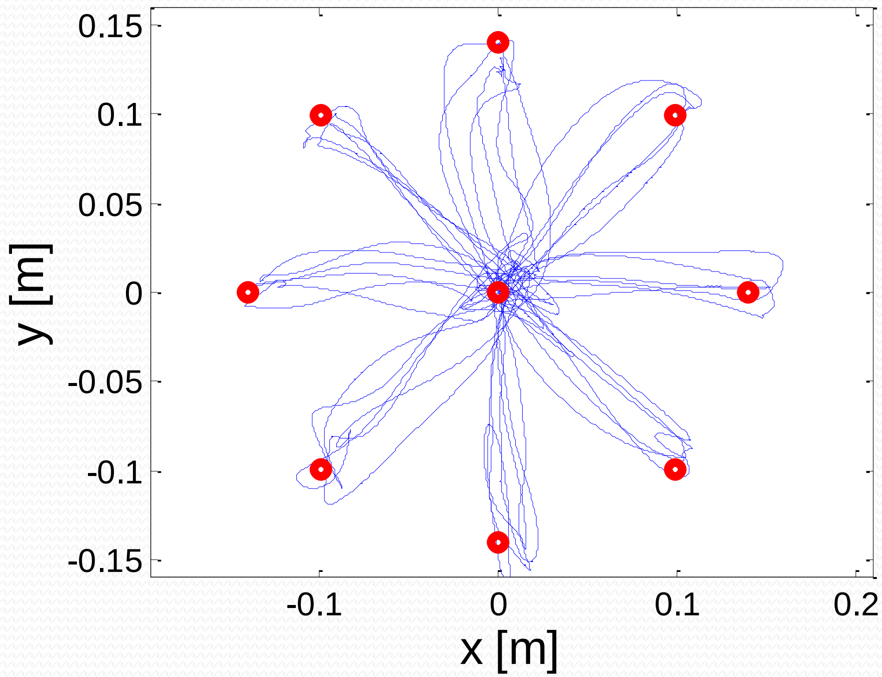
Assistive strategies with MIT-Manus

Results from a single-case study

(hemiplegic patient, 8 years old, hemorrhagic stroke)



First day of therapy



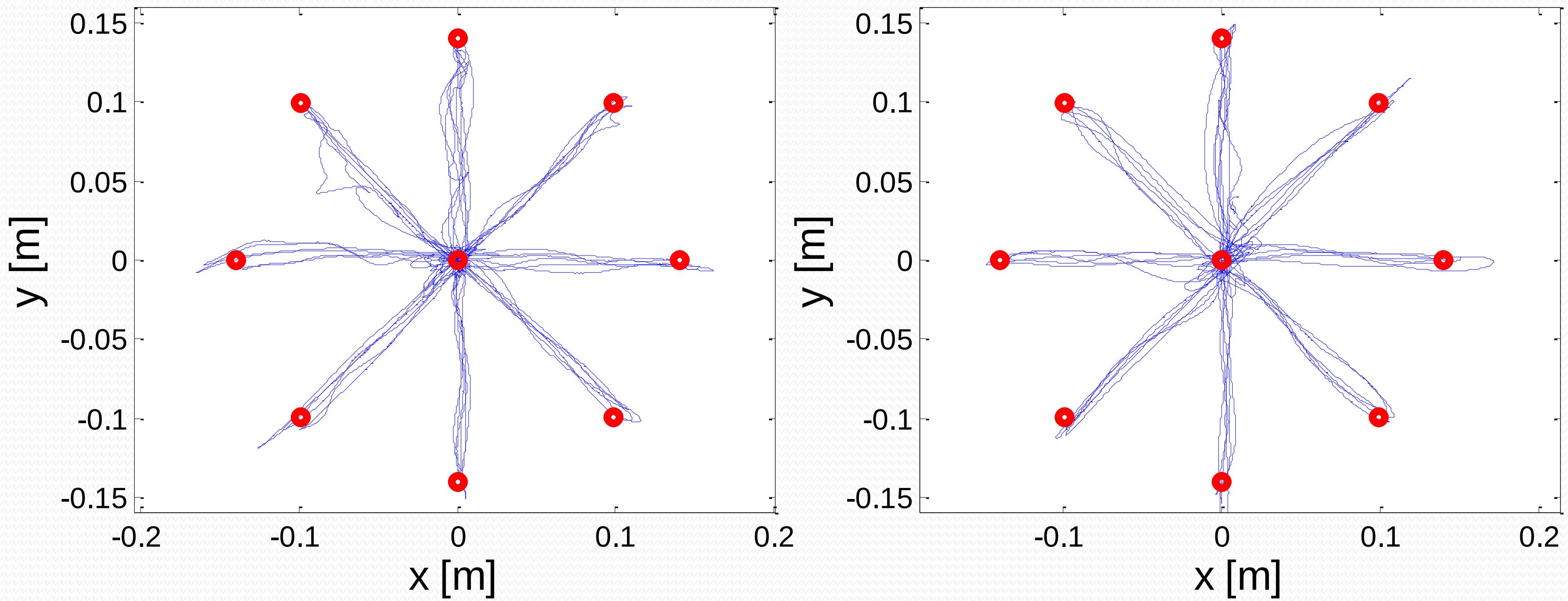
After three weeks

Unpowered mode

Assistive strategies with MIT-Manus

Results from a single-case study

(hemiplegic patient, 8 years old, hemorrhagic stroke)



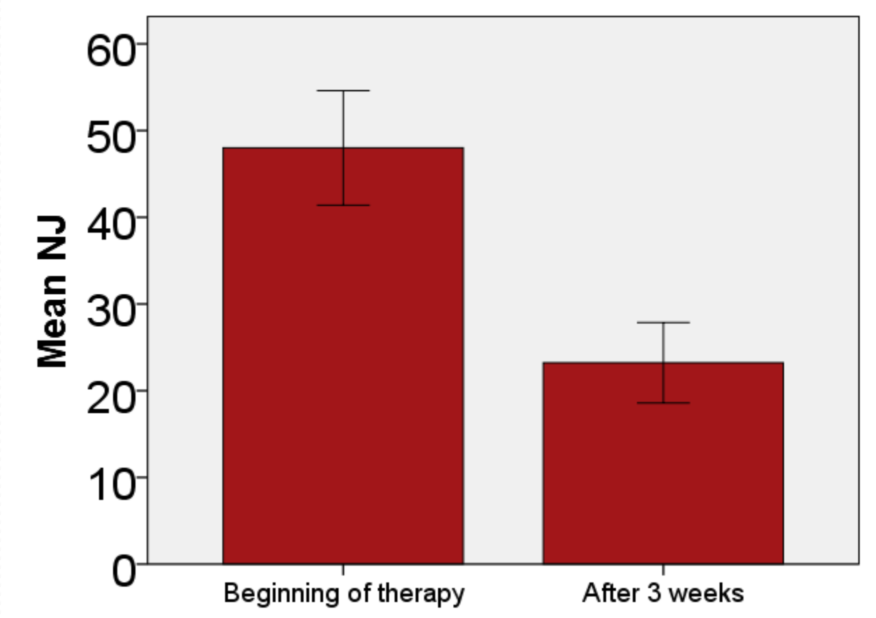
First day of therapy

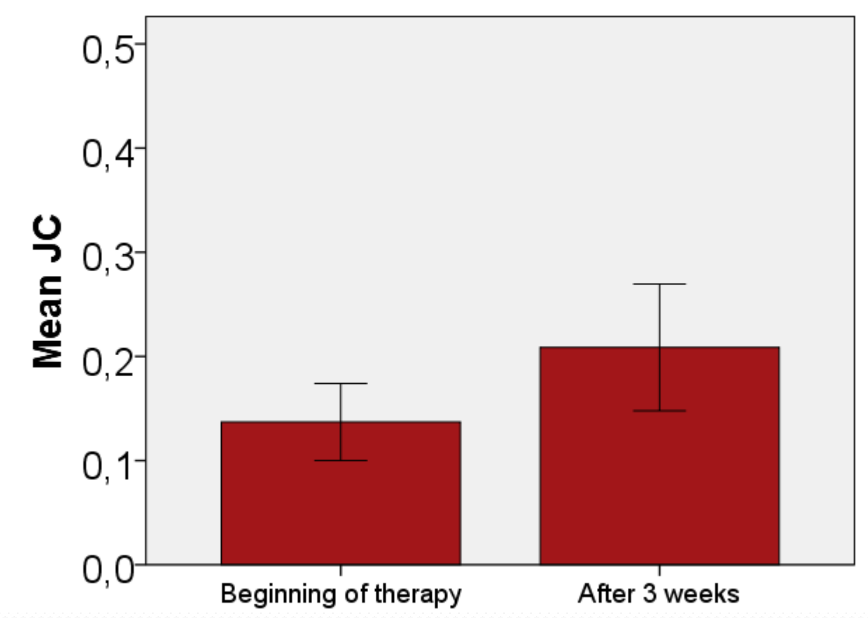
After three weeks

Powered mode

Assistive strategies with MIT-Manus

Results from a single-case study
(hemiplegic patient, 8 years old, hemorrhagic stroke)





Improvements in the trained task (planar reaching)

Normalized Jerk, a measure of "non-smoothness"

Improvements in an untrained task (circle-drawing)

Joint Correlation, a measure of coordination between shoulder and elbow joint

Assistive strategies with Anklebot

Pediatric Anklebot:

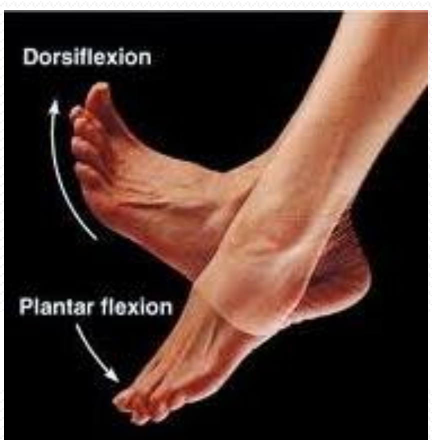
device for the rehabilitation of ankle joint, developed by our team in collaboration with the Massachusetts Institute of Technology.

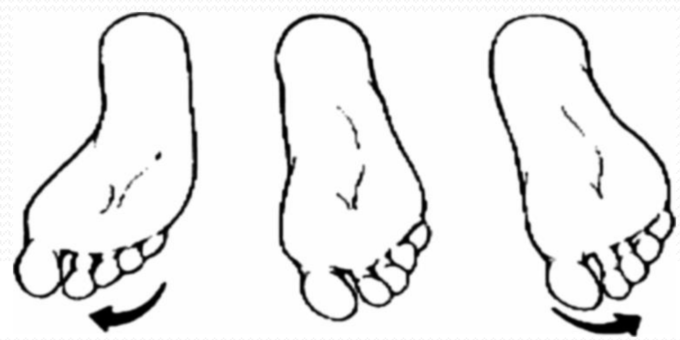
Assistive strategies with Anklebot

The pediatric anklebot alpha-prototype is a low-friction, backdriveable device with intrinsically low mechanical impedance that allows normal range of motion (ROM) in all three degrees-of-freedom of the foot relative to the shank during walking overground or on a treadmill. It allows:

- 25° dorsiflexion,
- 45° plantar flexion,
- 25° inversion,
- 15° eversion, and
- 15° internal or external rotation.

These limits are near the maximum range of comfortable motion for normal subjects and beyond what is required for typical gait.





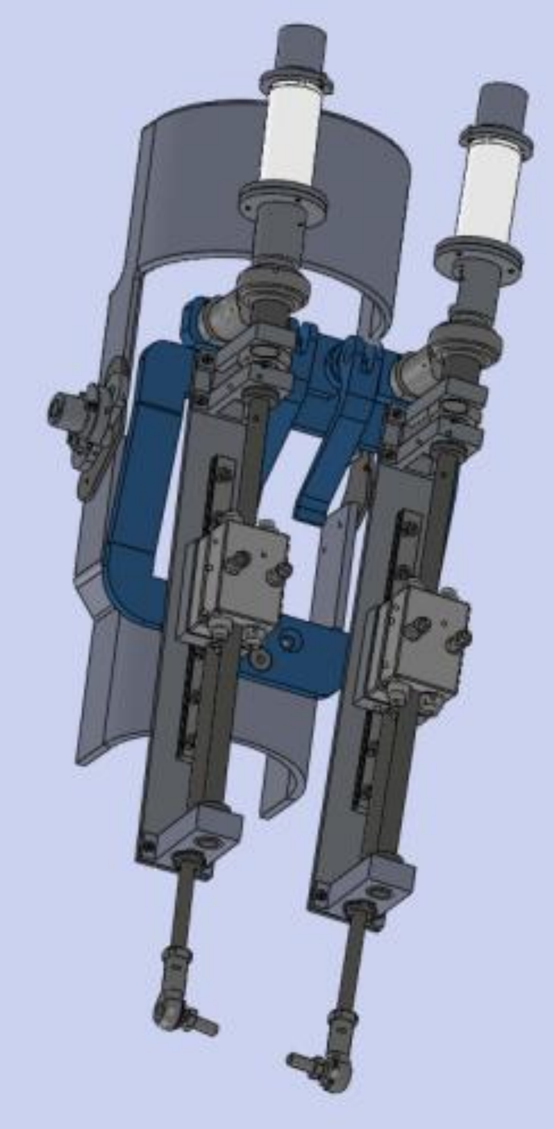
Assistive strategies with Anklebot

The robot provides independent, active assistance in two of these three degrees-of-freedom,

- dorsi-plantar flexion and
- inversion-eversion, and
- a passive degree-of-freedom for internal-external rotation.

The kinematic design consists of two linear actuators mounted in parallel such that if

- both push or pull in the same direction, a dorsi-plantarflexion torque is produced at the ankle
- if the two links push or pull in opposite directions, inversion-eversion torque results.



Assistive strategies with Anklebot

The device can deliver:

- a maximum torque ~7.21 N m in dorsi-plantarflexion and
- ~4.38 N m in inversion-eversion.

It also possesses minimal friction and inertia to maximize the backdriveability.

The Anklebot is actuated by two brushless DC motors.

Motion and torque information is provided by two sensors:

- a mini-rail linear encoder mounted in parallel with the motors used to estimate ankle angle in plantar-dorsiflexion and inversion-eversion.
- The second is a rotary encoder.

Assistive strategies with Anklebot

Measure of the stretch reflex spatial threshold EMG triggered

GOAL: measure the spasticity of the ankle joint in children with Cerebral Palsy with a robotic device

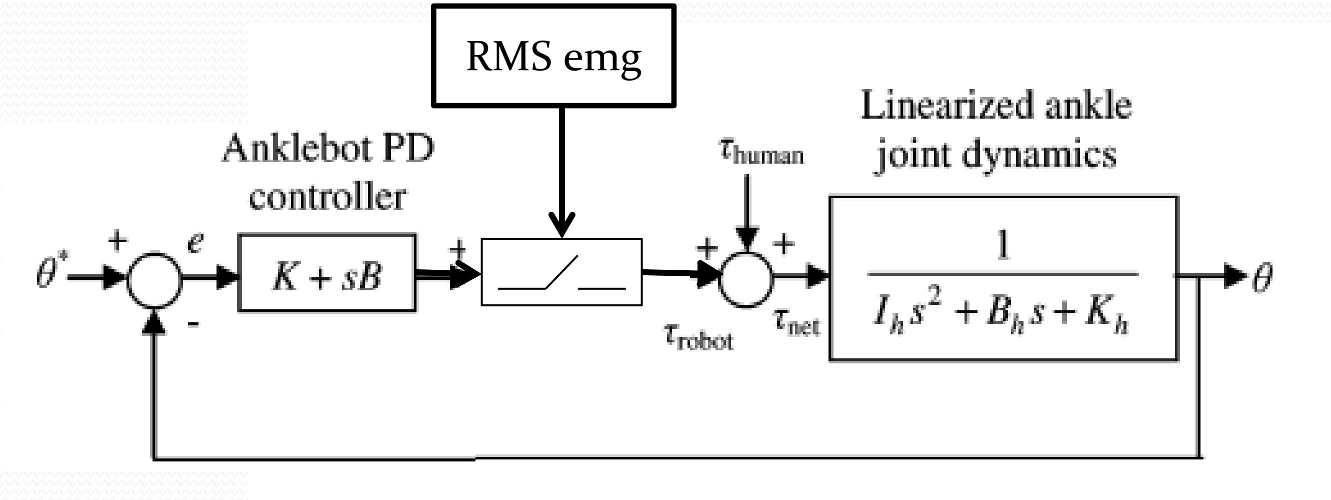
METHOD: elicitate the stretch reflex at different speed and measure the angle corresponding to the onset of the reflex by means of the SEMG signal (Mullick et al, 2012).

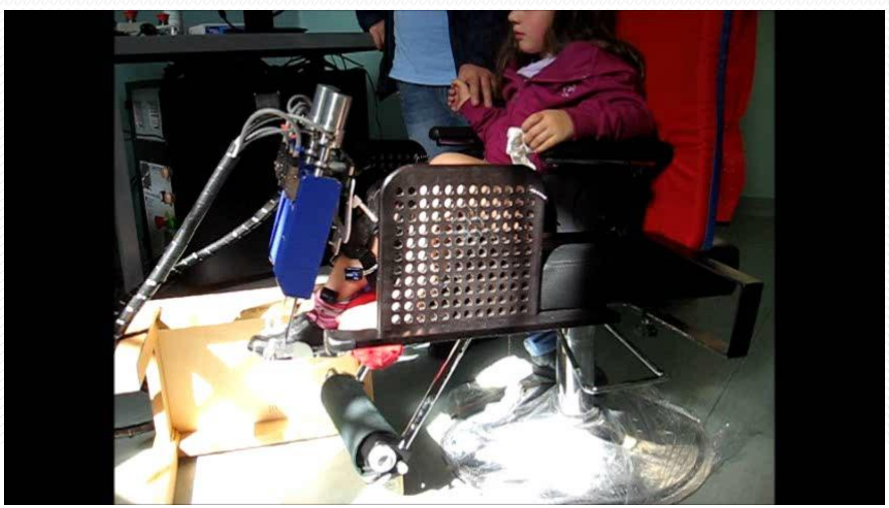
PROBLEM: before the elicitation, the muscle has to be relaxed in order to measure the onset correctly

SOLUTION: adopt a “reversed” EMG-triggered strategy, i.e., the robot has to be actuated only when the muscles are relaxed

Assistive strategies with Anklebot

Measure of the stretch reflex spatial threshold EMG triggered





BIOMECHANICS:
Lecture #7 – Robot Mediated Therapy

Facoltà di Ingegneria
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