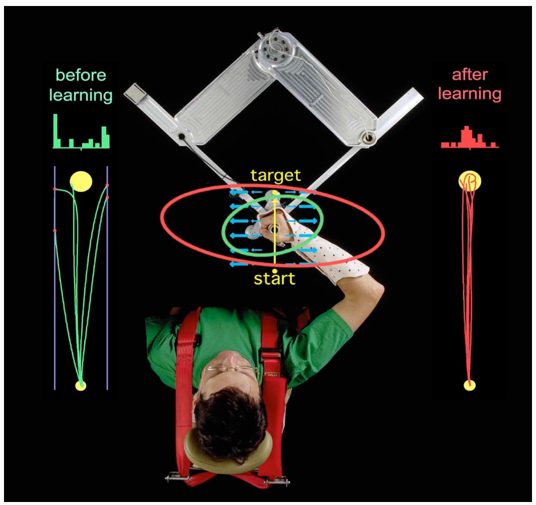
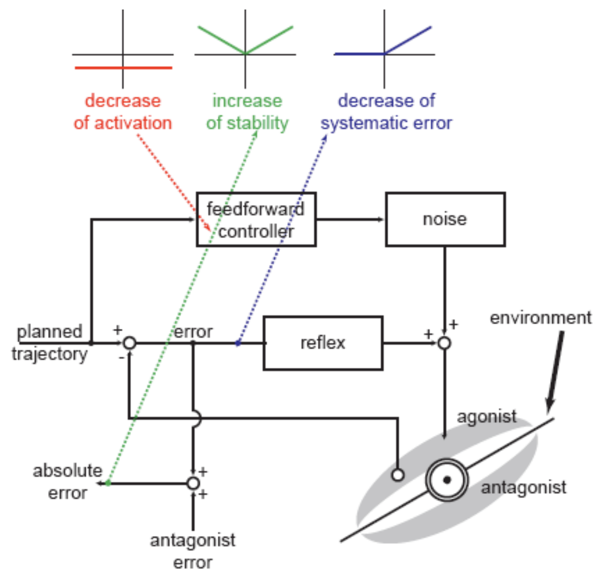
HUMAN ROBOTICS

neuromechanical control and learning





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WHY STUDY MOTOR CONTROL?

- how do humans perform skilful actions and continually improve performance with such ease?
- how do children develop complex motor behaviours?
- how could one best assist persons whose ability to control movement has been impaired by neurological disease or injury?
- much is unknown about the neural mechanisms involved in the control and learning of motor tasks

NEUROSCIENCE FRUSTRATION

- after more than 100 years of research in neuroscience, we are still unable to fully understand neural control
- in some cases, we become less sure about the neural mechanisms as we study them more
- we are even unclear about the way neurons code and carry information
- neuroscience textbooks such as Kandel&Schwartz just become fatter and fatter

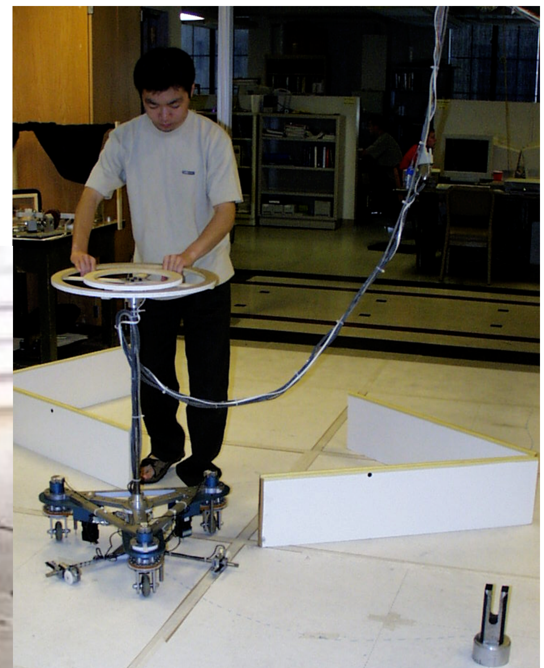
NEUROSCIENCE: FROM FRUSTRATION TO CONSTRUCTION

- a constructive approach: if we are not able to understand as well as in physics, we may still be able to reproduce and predict some behaviours
- this will already be useful to neurorehabilitation and may lead to new products for everyday life
- this could lead to thinner textbooks: a few models to summarise many behaviours

COLLABORATIVE ROBOTS

intelligent assistive devices for the industries and for everyday life

our Collaborative Wheelchair can provide disabled assistance corresponding to their needs and capabilities



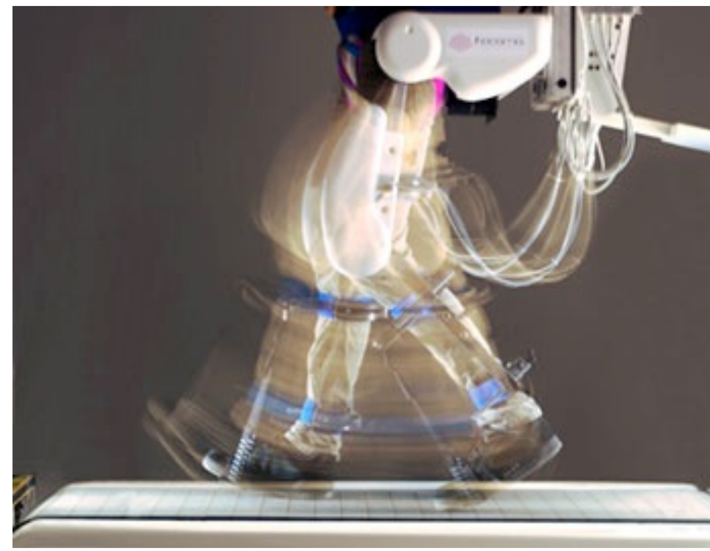
devices to help workers manipulating heavy and large objects easily developed by Stanley Cobotics and Northwestern University, USA

COLLABORATIVE ROBOTS

robot systems for medical interventions

COLLABORATIVE ROBOTS

virtual reality based training systems
using haptic interfaces



Lokomat for walk rehabilitation
from Hocoma, Switzerland

microsurgery training system in our lab at NUS

COLLABORATIVE ROBOTS

- in recent years many kinds of robotic systems have been developed to collaborate with humans
- understanding the control of the human body when interacting with collaborative robots could significantly improve their performance

HUMAN MANIPULATION AS A FASCINATING ROBOTIC SYSTEM

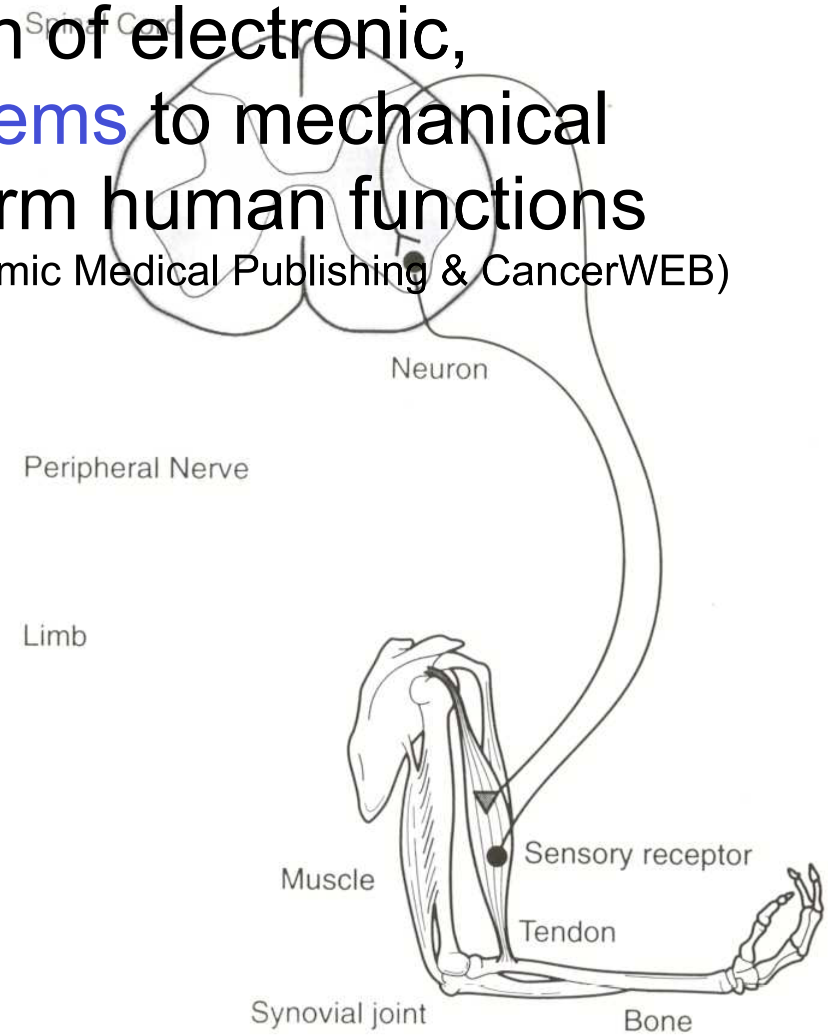
- a system level approach, considering the biomechanics, sensors and control
  -> human robotics

- develop physiological models relying on measurable variables -> testable models

- that could produce similar robot behaviours
  -> implementable

HUMAN ROBOTICS

- Robotics: The application of electronic, computerised control systems to mechanical devices designed to perform human functions
(on-line Medical Dictionary, © 1997-98 Academic Medical Publishing & CancerWEB)



- skeleton as the mechanical structure
- muscles as actuators
- neural sensory receptors
- neurons and brain to control behaviours

HUMAN ROBOTICS

- a system level synthesis of biomechanics and neural control (brain *and* hand)

- neuroscience is more than computer science: considering the cognitive processes only may lead to misinterpretations -> must also consider the biomechanics and dynamics

- biomechanics/forces is not enough: sensors, feedback, neural processes and a correct balance are required

HUMAN ROBOTICS

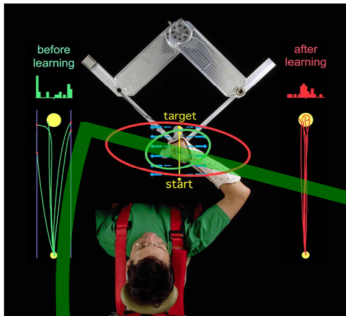
- a system level synthesis of biomechanics and neural control (brain *and* hand)

- computational models as tool to investigate how the brain functions in learning to control movement

- to control neural prostheses or use in rehabilitation -> towards cyborgs

neuroscience robotics control

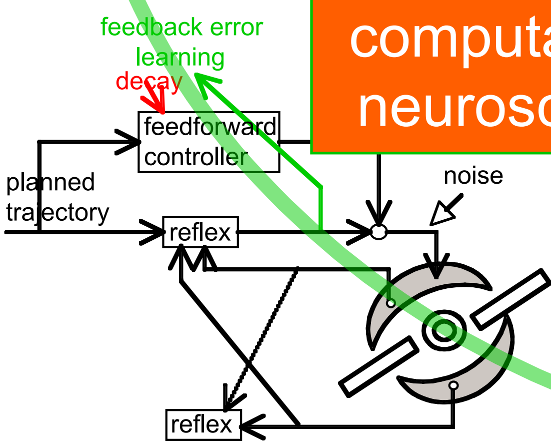
human robotics



human motor control

virtual reality rehabilitation

computational neuroscience

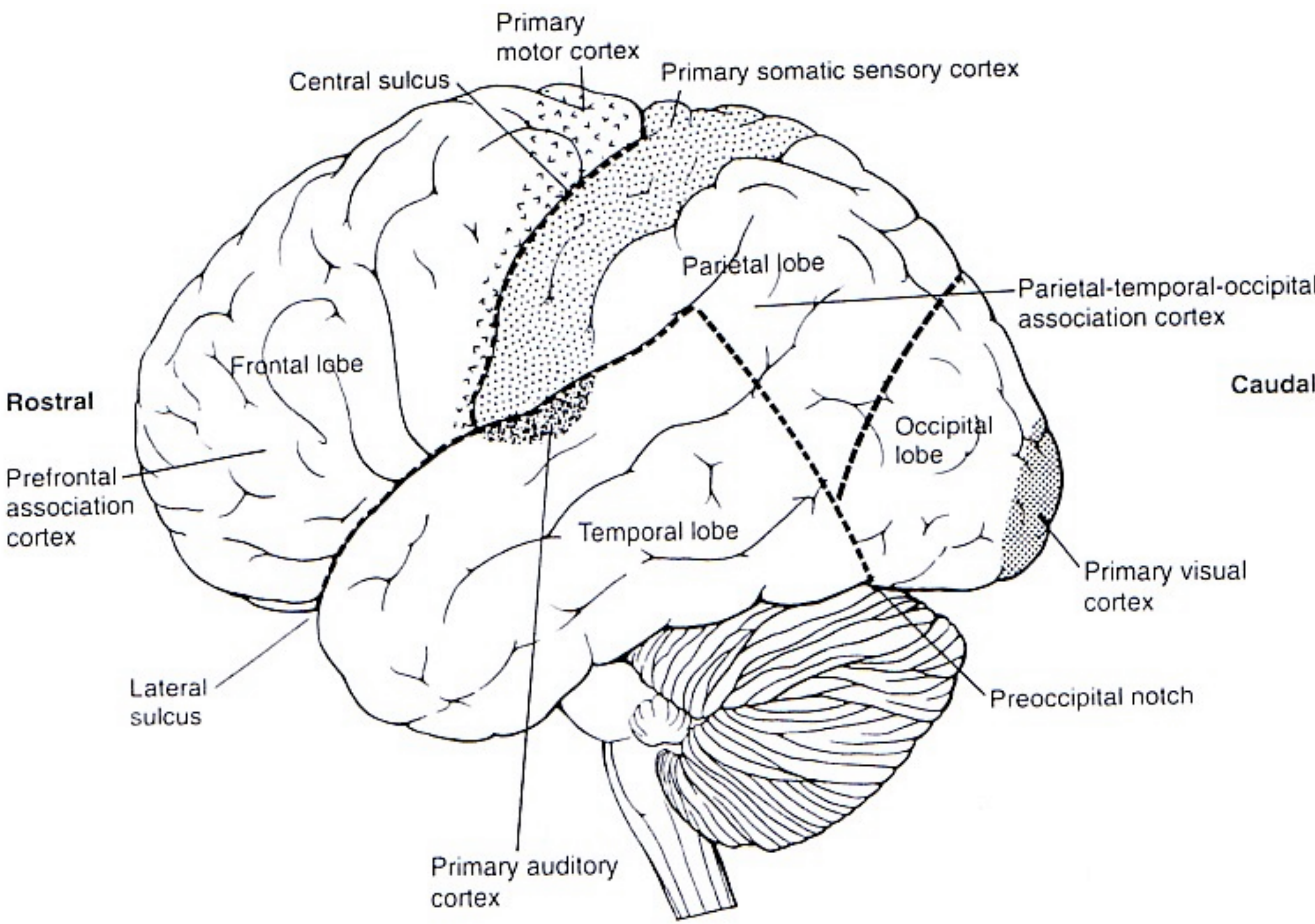


assistive devices

virtual reality based surgery training

https://www.imperial.ac.uk/human-robotics

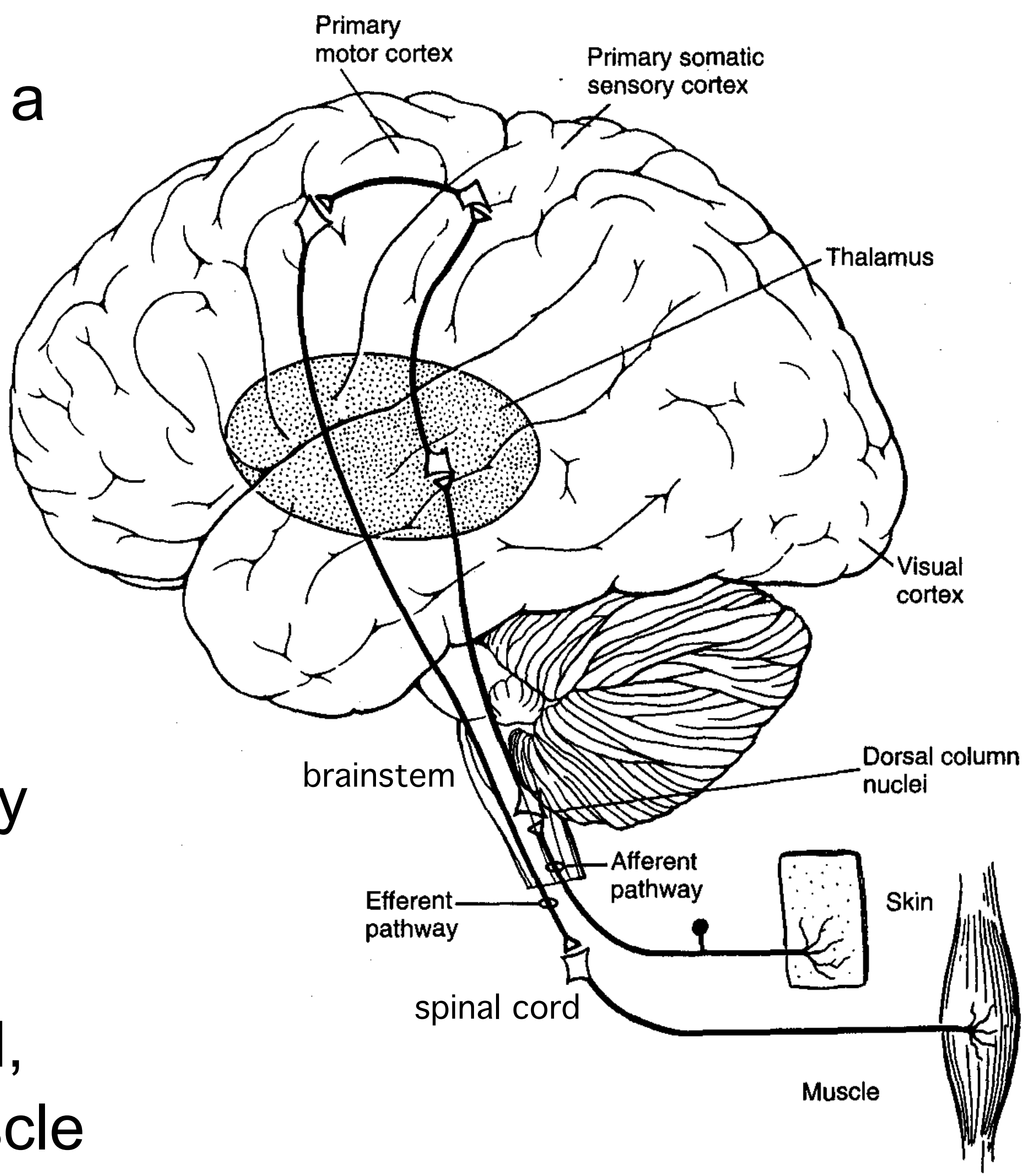
DIVISIONS OF THE CORTEX



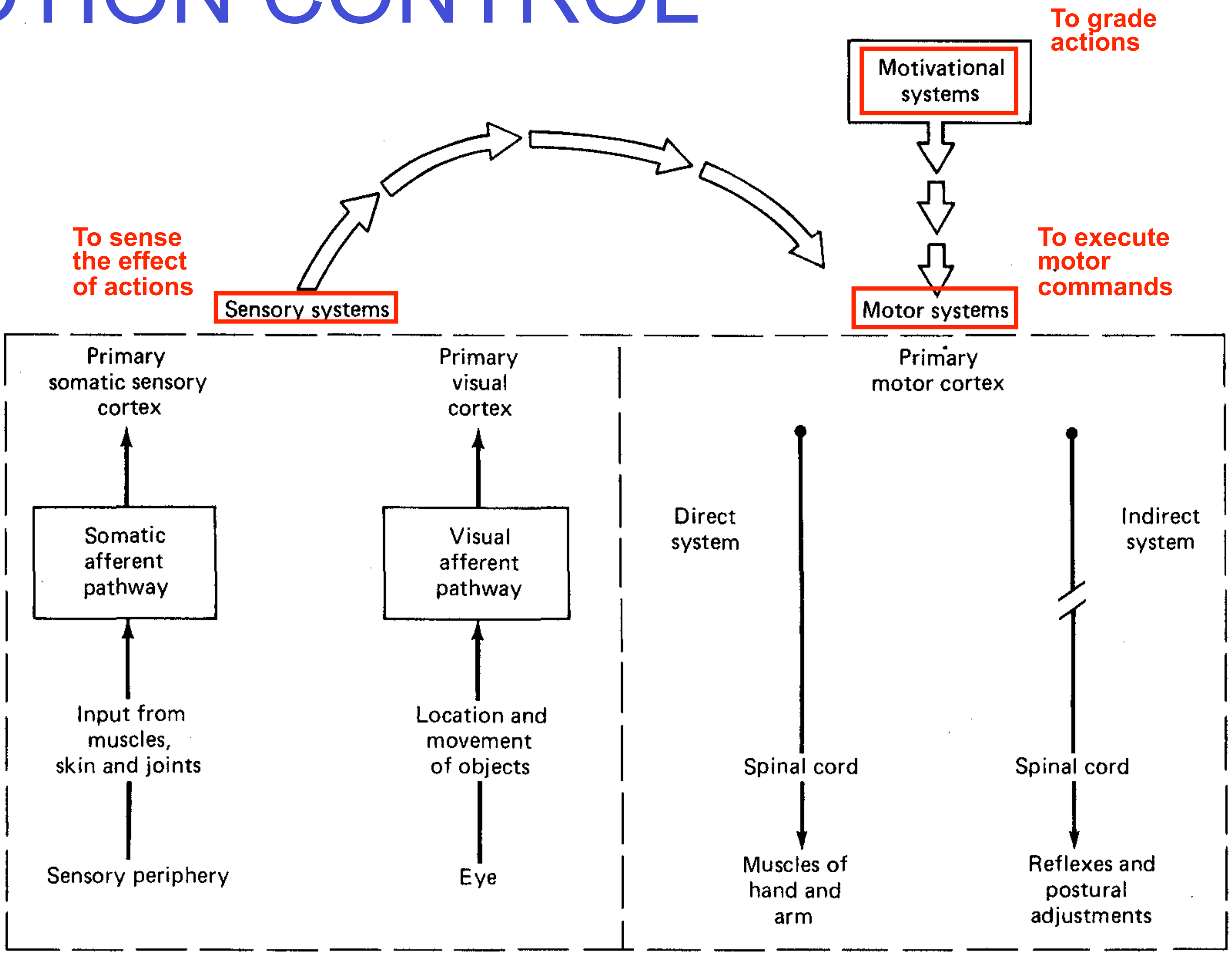
MOVEMENT GENERATION

- sensory input ascends through the spinal cord to a synaptic relay in the brainstem, then to a synaptic relay in the thalamus, eventually reaching the primary somatic sensory cortex

- the direct motor pathway descends from the primary motor cortex through the brainstem to the motor neurons of the spinal cord, and from there to the muscle



MOTION CONTROL

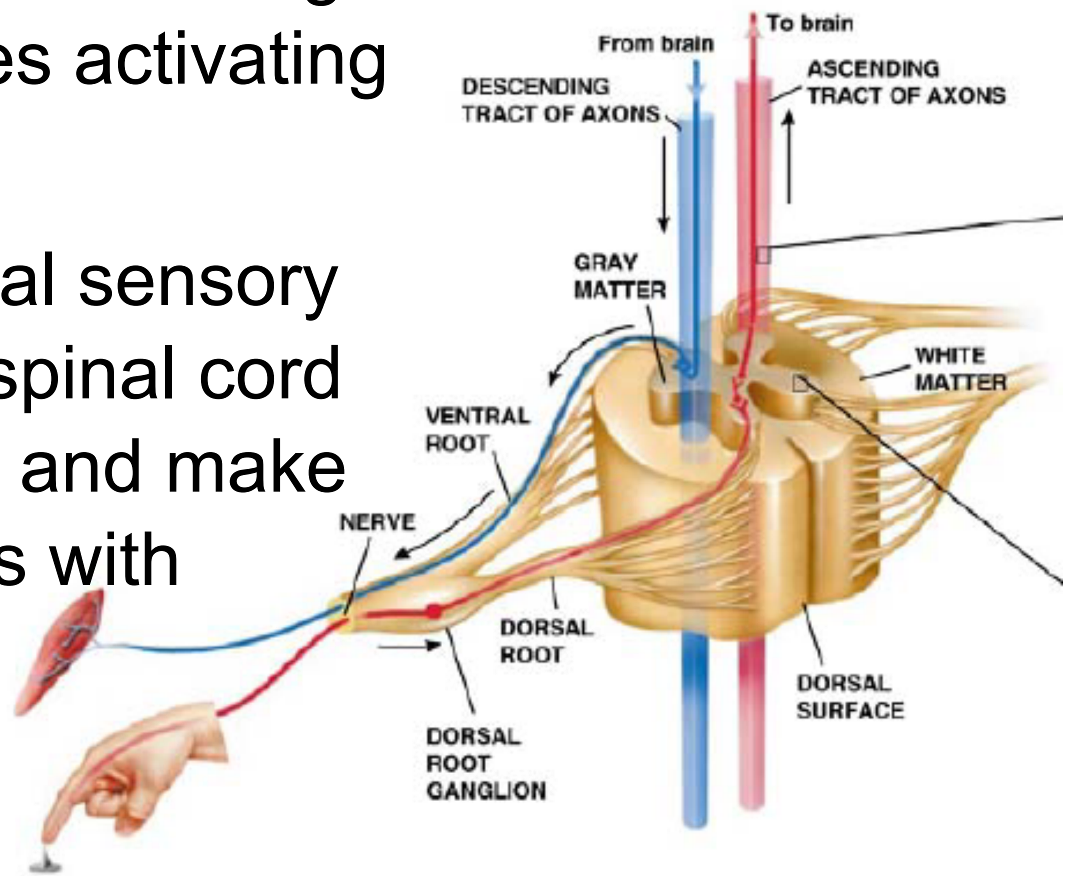


DECENTRALISED CONTROL

- the motor systems must consider the kinematics and dynamics of muscles, bones and joints, as well as activate the redundant multi-muscle systems
- the motor systems are organised as a hierarchy of control levels, each provided with the sensory information for the functions it controls
- parallel control of muscles can be carried out by control centres in the brain, brainstem and spinal cord, although the actions of lower control centres can be modulated by higher control centres

SPINAL ORGANISATION

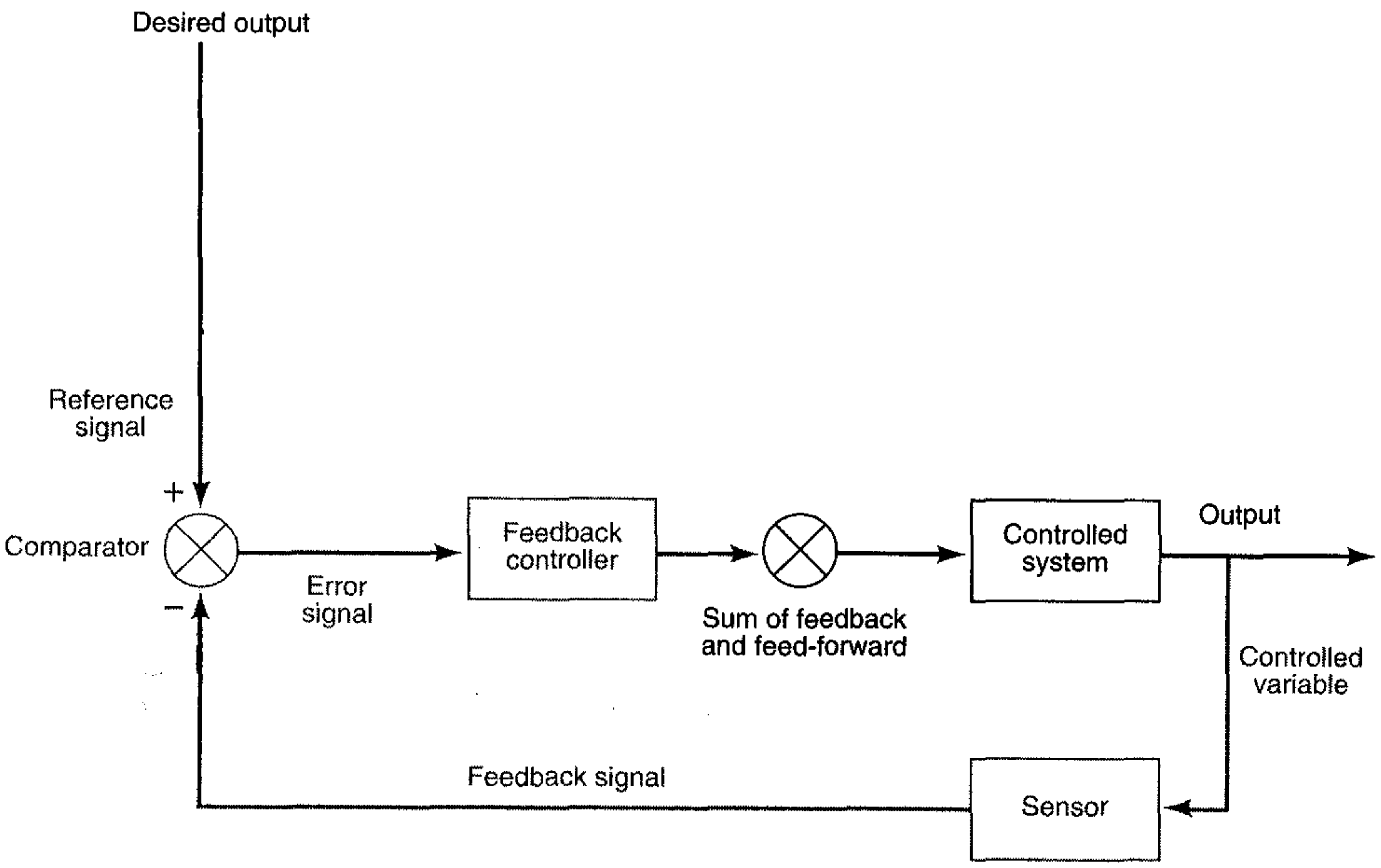
- axons from motoneurons leave the spinal cord through ventral nerve roots and become bundled together into peripheral nerves activating muscles
- axons from peripheral sensory receptors enter the spinal cord through dorsal roots and make synaptic connections with interneurons



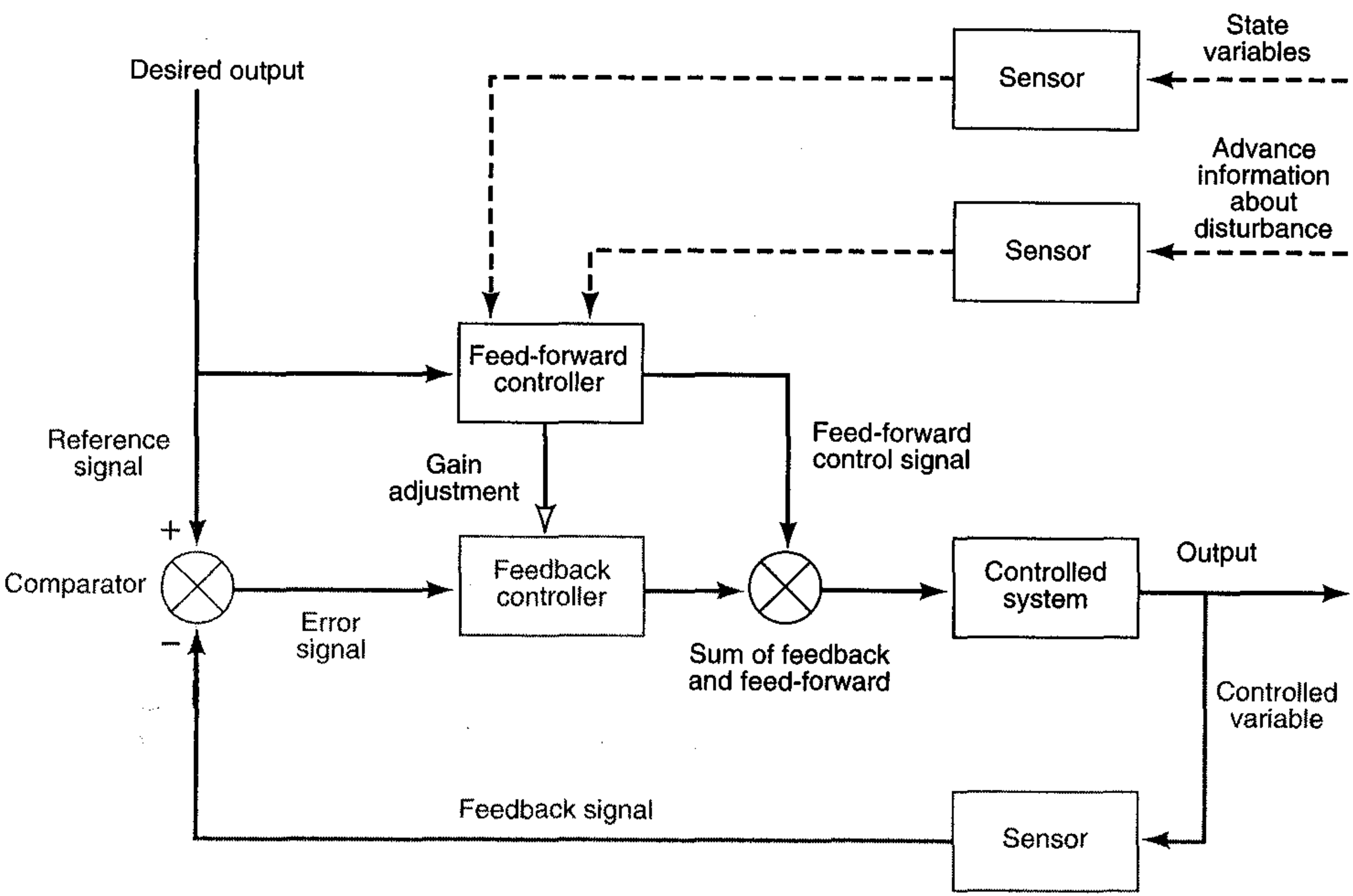
FEEDBACK MECHANISM

- feedback mechanism: sensory information is used to control a process
- examples: spinal reflexes, visually elicited corrections to grasp an object
- feedback is not sufficient to control actions well, e.g. visual feedback requires at least 100-200*ms*, while fast arm movements may last only 150-200*ms*

FEEDBACK CONTROL



FEEDFORWARD CONTROLLER



FEEDFORWARD CONTROLLER

- feedforward mechanism: descending motor command is elicited according to a plan of the expected task dynamics
- evidence through large fiber neuropathy* patients who cannot sense their limb position or motion, have neither tendon reflexes nor tactile sensation#
- they cannot stand when vision is prevented
- compensation through feedback and feedforward: the movements are worse when vision is prevented before the movement

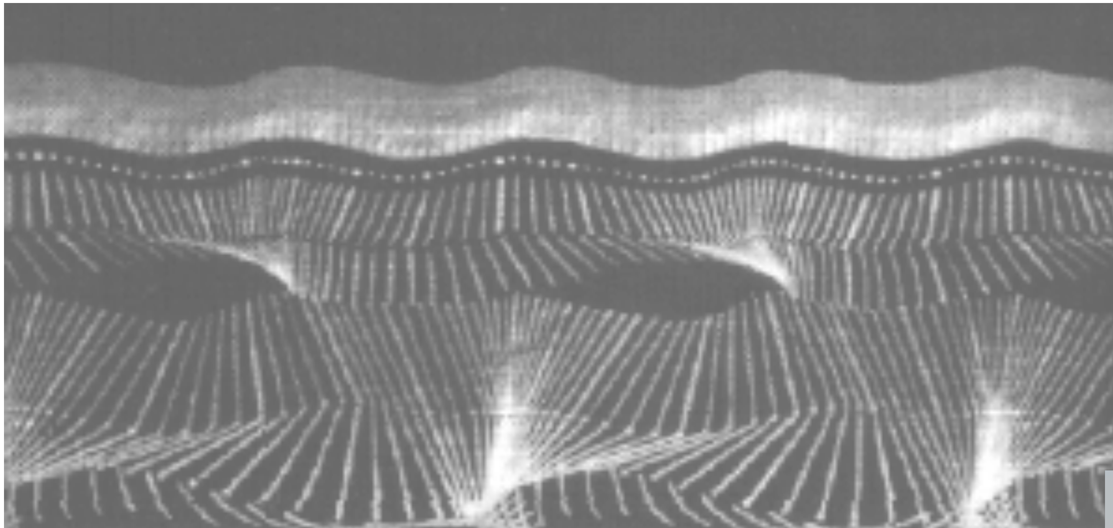
* degeneration of large afferent fibers carrying the output of muscles and joint sensors

\# these patients can feel temperature and pain, carried by small-diameter afferent fibers

TOOLS TO MEASURE MOTOR BEHAVIOUR

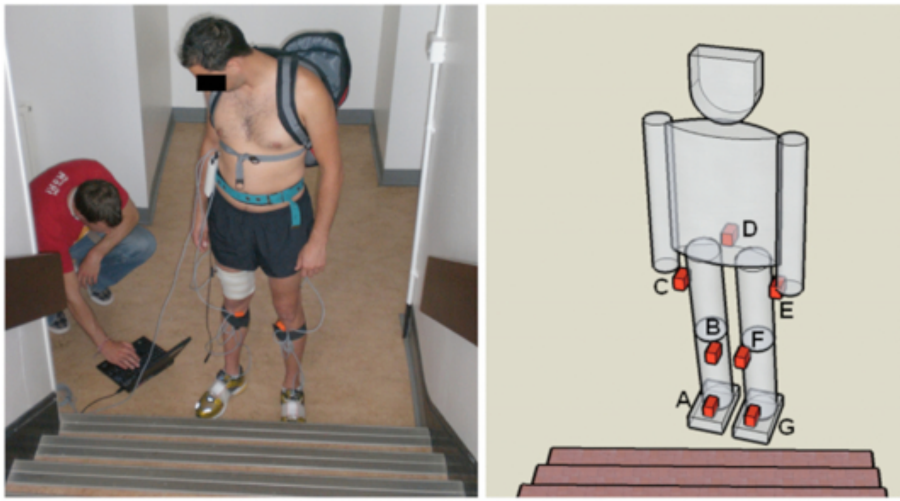
- camera-based system to record trajectories
- IMU inertial measurement units
- EMG to evaluate motor commands
- haptic interface to create dynamic environments
- fMRI to estimate brain activity

KINEMATIC MEASUREMENT

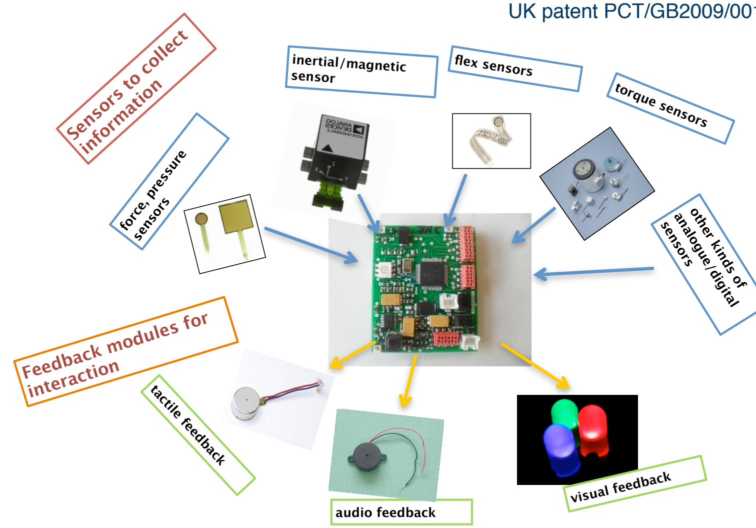


- camera based system first used by E Marey in ~1880
- still used in motion capture
- occlusion of markers solved with electromagnetic sensors

INERTIAL MEASUREMENT UNIT

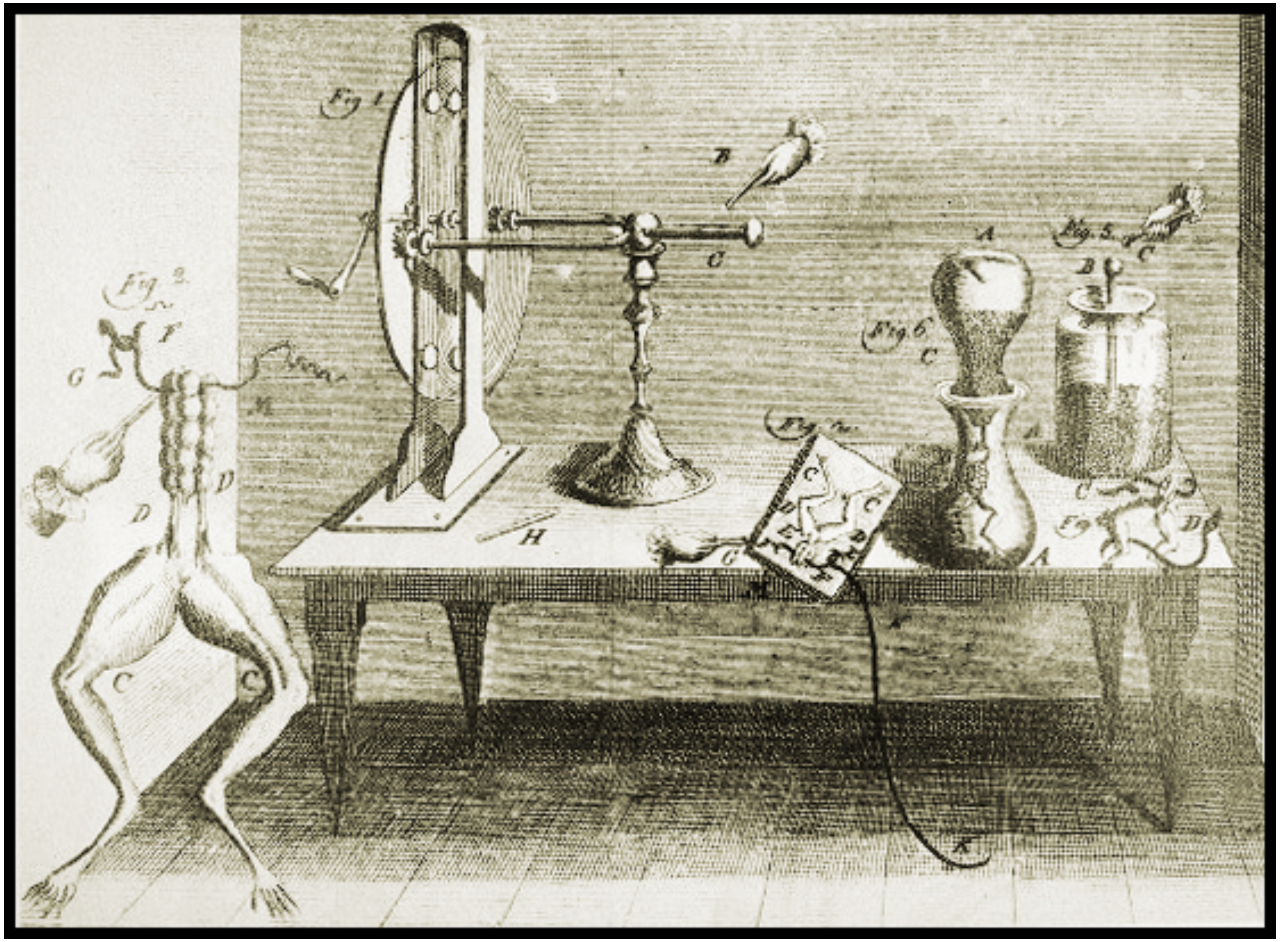


UK patent PCT/GB2009/001449



- IMU: involve a combination of accelerometers, gyroscopes and magnetometers
- to measure velocity, orientation and altitude
- +: cheap, small and simple
- -: error integrates with time

ELECTROMYOGRAPHY (EMG)

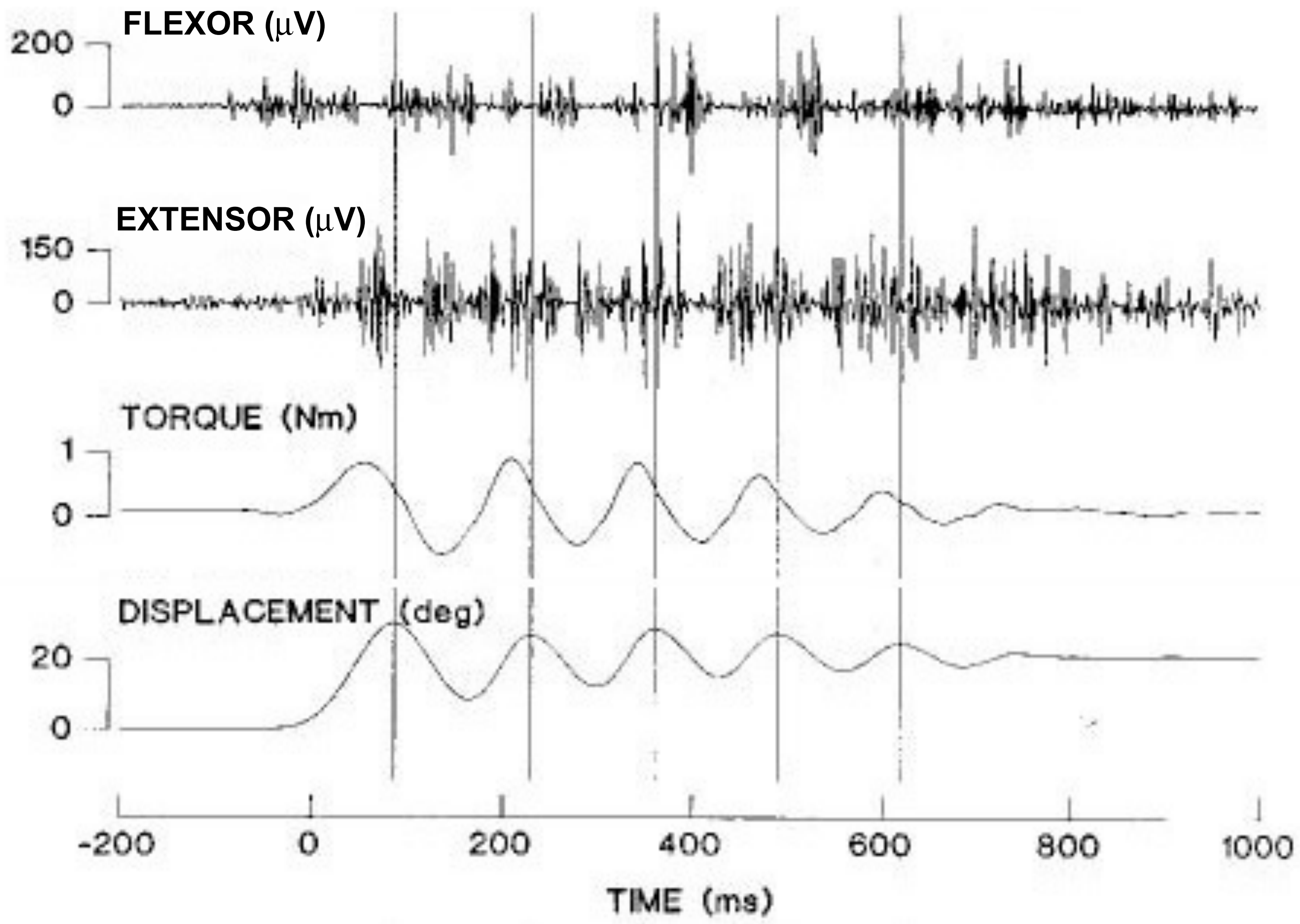


motor commands are transmitted through changes of electrical potential (Galvani, 1780)

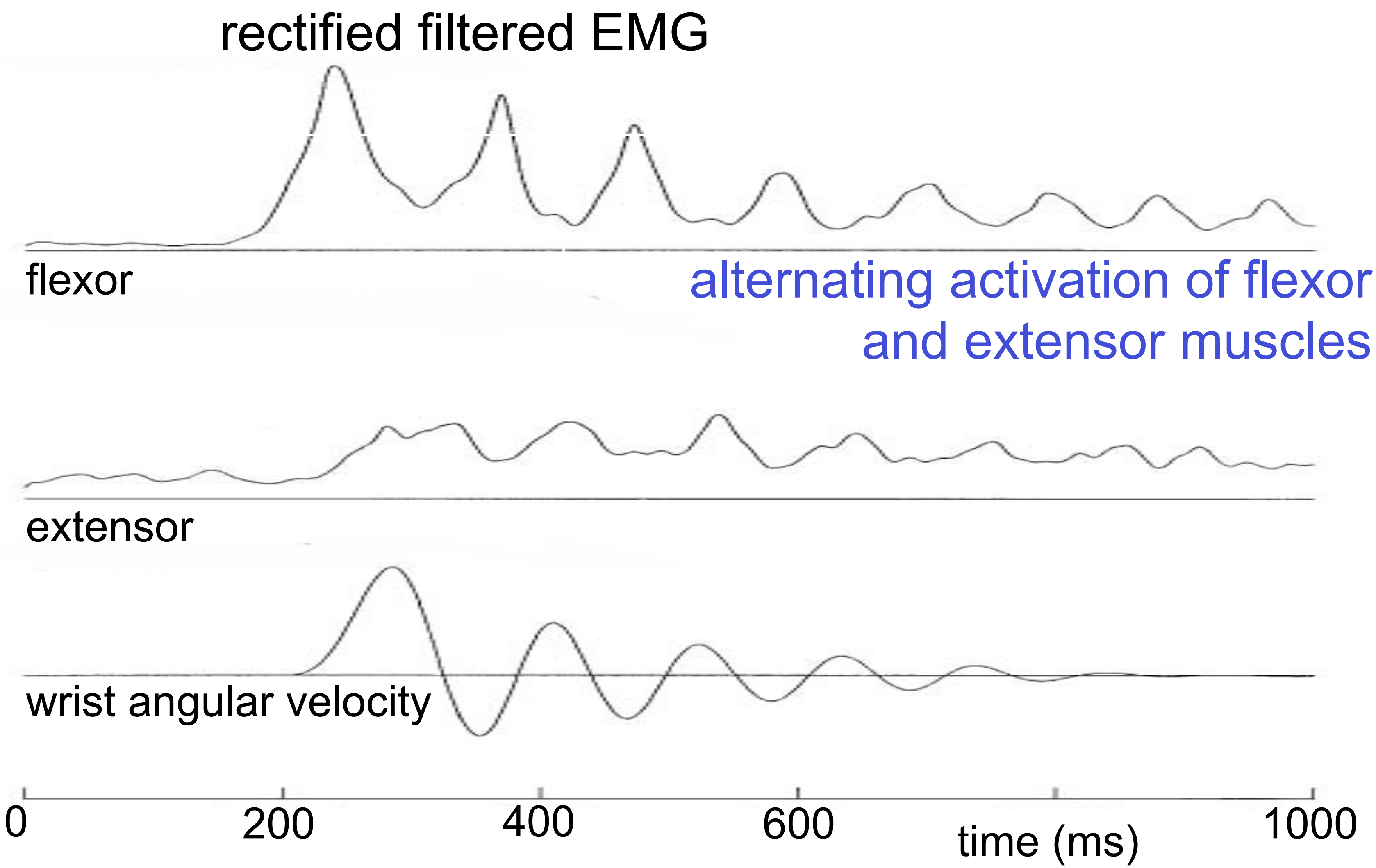
ELECTROMYOGRAPHY (EMG)

- measure the voltage between two electrodes
- can be placed on the skin: surface electrodes to measure the activation of an area of the whole muscle
- large variability as muscle fibres are not activated in the same sequence for repeated movements
- mean over several (at least 10) trials to improve reliability
- within the muscle: better signal as signals from other muscles (cross-talk) are avoided
- in the muscle: the smaller the electrode the more selective the signal, thus may not represent overall muscle activity

EMG DURING WRIST MOTION

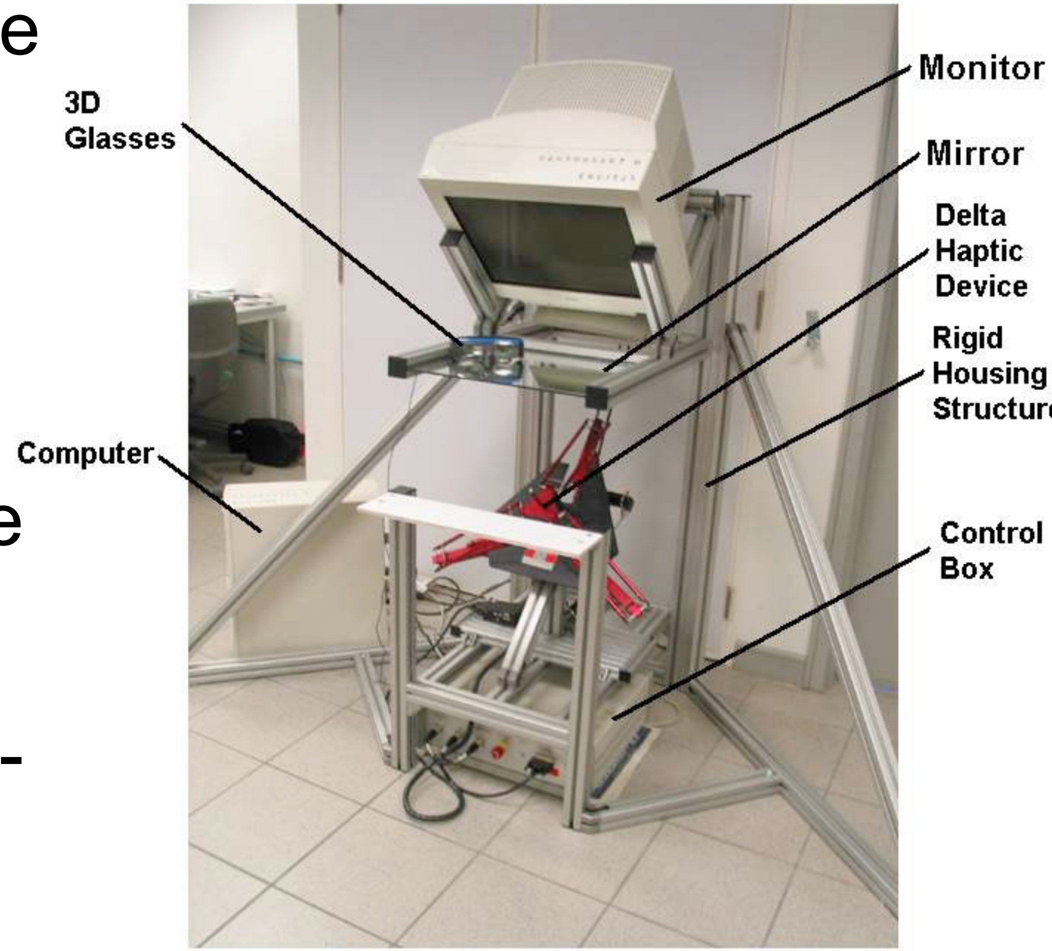


EMG DURING WRIST MOTION

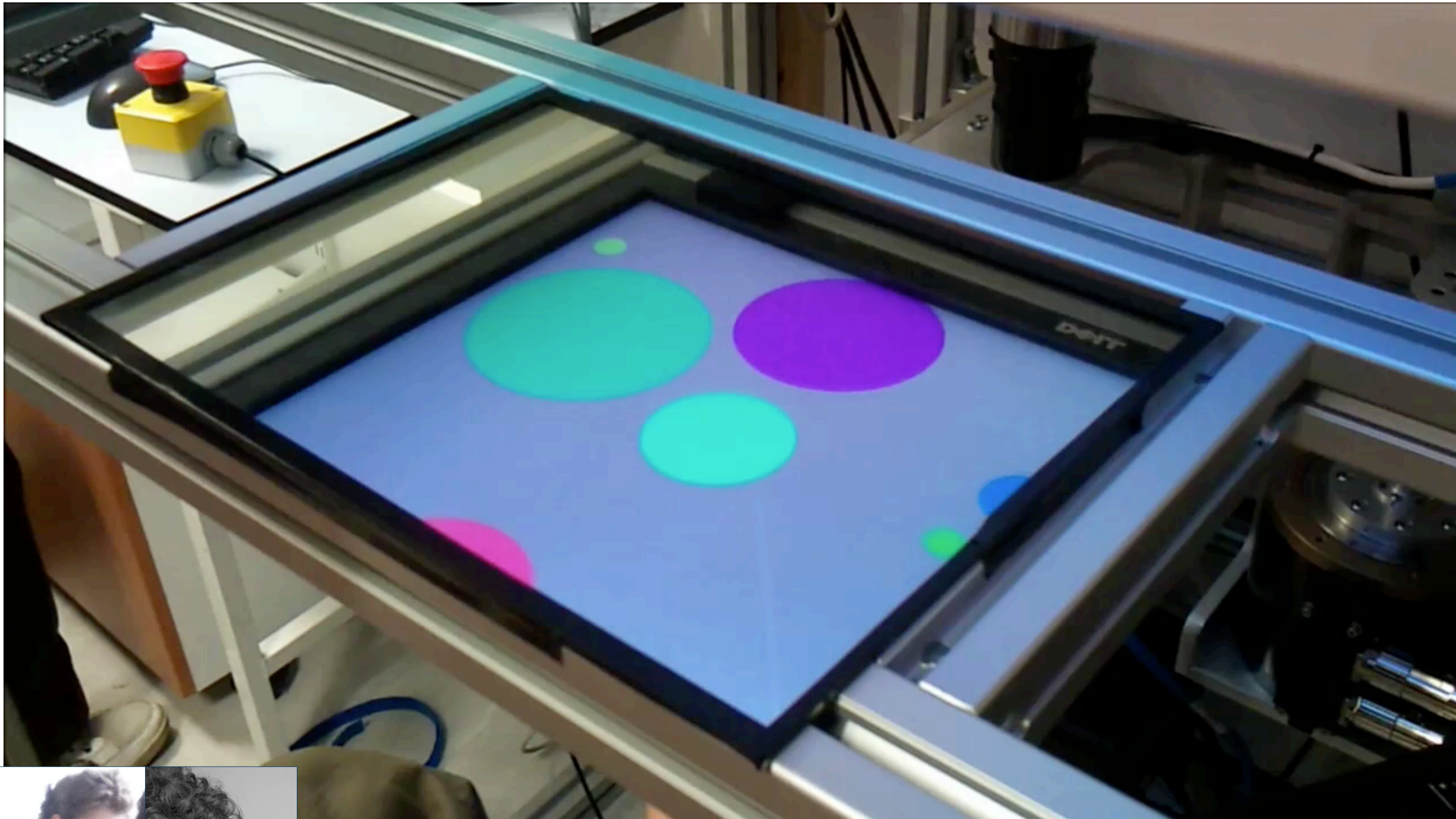


VIRTUAL REALITY WORKSTATION

- safe and reproducible computer-controlled environment
- 3D visual feedback, 6DOF force/torque feedback through the haptic interface
- no distortion of hand-eye coordination



3*DOM* TO STUDY ARM CONTROL



UCL

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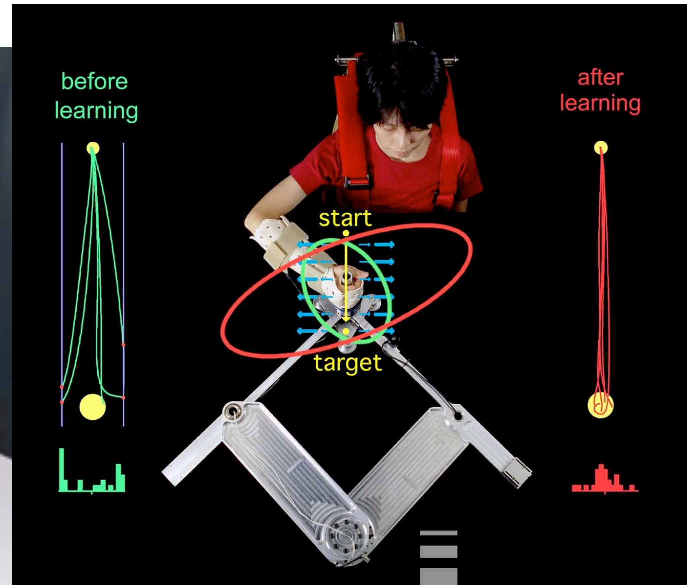
[Klein et al. 2014 IEEE Transactions on Haptics]

FUNCTIONAL MAGNETIC RESONANCE IMAGING (fMRI)

- brain imaging is normally used to observe tissue, detect tumours etc
- MRI has become the major imaging modality, has spatial resolution in order of mm and temporal resolution in order of seconds (better than PET)
- fMRI detects blood oxygenation in specific areas, which is assumed to covary with brain activity
- activity related to a specific action is detected as difference from the activity at rest
- fMRI does not reveal the brain mechanisms per se

fMRI COMPATIBLE INTERFACE



• how the brain controls motion and deals with computer-controlled dynamic environments

• MRI compatible robotic technology

Imperial College
London

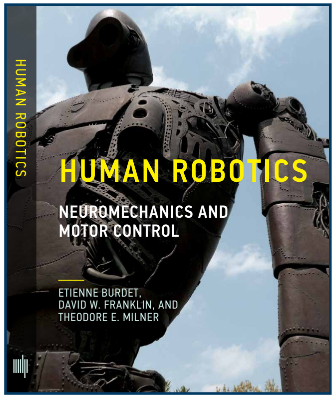
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

fMRI COMPATIBLE INTERFACES

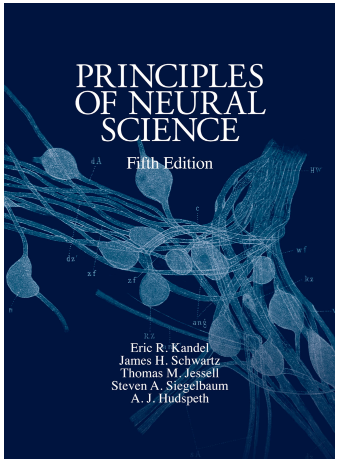
- transmission from outside the MR room using a hydraulic transmission
- we have developed interfaces for the wrist, multijoint arm, hand and tactile sensing, which are used by neuroscience groups in Japan, Italy and in the UK

[Gassert et al. IEEE TMECH 2006]

RECOMMENDED LITERATURE



- this course gave rise to the book “Human Robotics” by MIT Press



- the book “Principles of Neural Science” gives simple access to neuroscience

- technical aspects are covered by standard robotics and nonlinear control textbooks

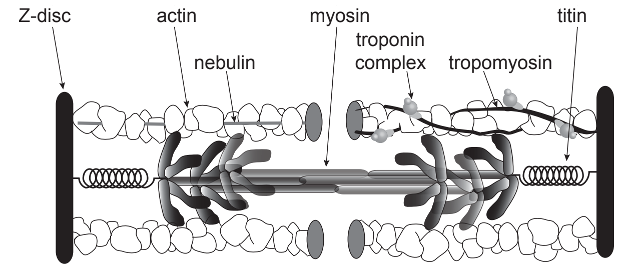
- related physiology is contained in papers from J of Neurophysiology, J of Neuroscience, Biological Cybernetics, Nature, Science, Experimental Brain Research etc

HOW DO WE CONTROL MOTION?

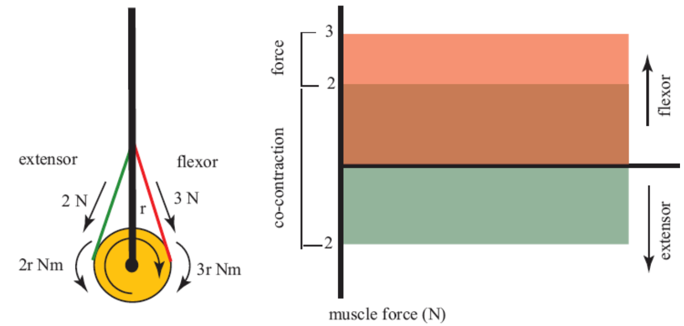


- imagine trying to learn tennis
- initially you cannot contact the ball with the racket, but gradually with practice you improve and can play
- what has changed that made you a player ?

HUMAN ROBOTICS

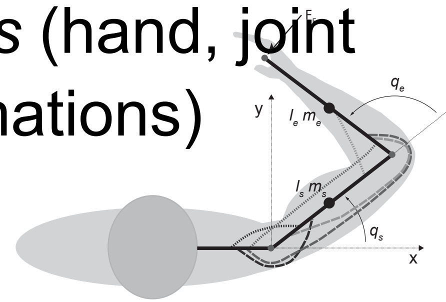


- *muscle mechanics and control* (Huxley cross-bridge attachment model, viscoelasticity)



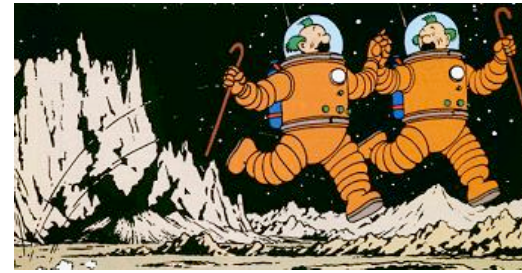
- *single-joint neuromechanics* (tunable mechanical properties and reflexes)

- *multi-joint multi-muscle kinematics* (hand, joint and muscle spaces and transformations)

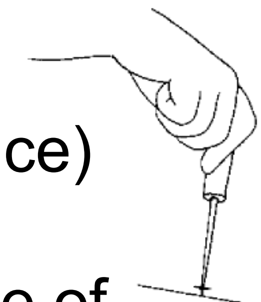


- *multi-joint dynamics and control* (rigid body model and mechanical impedance, redundancy)

HUMAN ROBOTICS

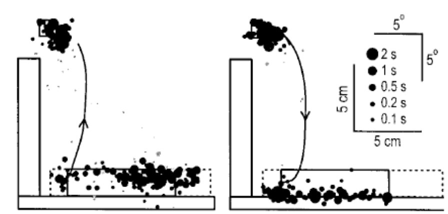


- *motor learning and memory* (motor adaptation, iterative and nonlinear adaptive control)



- *motor learning under unstable conditions* (motor adaptation with mechanical impedance)
- *motion planning and online control* (evidence of planning phase, minimisation of error and effort, optimal control, motor primitives)

- *integration and control of sensory feedback* (Bayesian & active sensing, forward model)



- *applications in neurorehabilitation and robotics*

REQUIREMENTS/ ASSESSMENT

- take part to an experiment: select your experiment, then fill the Doodle for an appointment
- 5 tutorials (20%): to become familiar with the mathematical background necessary to grasp human neuromechanics
- written examination (80%): 3 questions based on understanding rather than on long mathematical developments

TUTORIALS

- Tutorial 1: physiology (deadline 1/2)
- Tutorial 2: kinematics and redundancy (->8/2)
- Tutorial 3: dynamics and linear control (->15/2)
- Tutorial 4: nonlinear control and learning (-> 22/2)
- Tutorial 5: sensory prediction (-> 8/3)