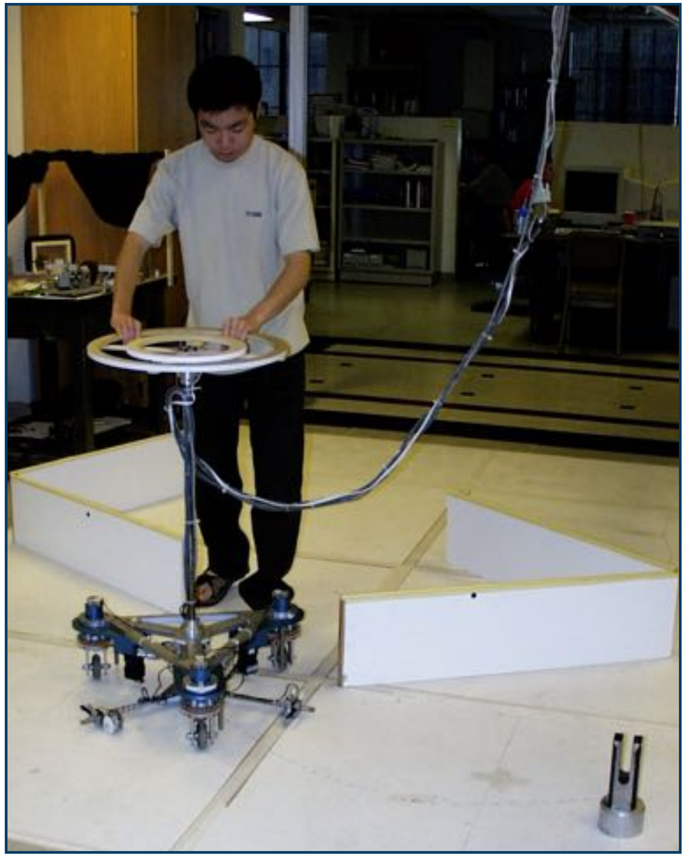
COLLABORATIVE ROBOTS FOR MOBILITY ASSISTANCE AND REHABILITATION

Etienne Burdet

Imperial College
London

COLLABORATIVE ROBOTS - COBOTS

intelligent assistive devices for
the industries and for everyday life



from Colgate&Peshkin’s research at Northwestern U.
to the successful spin-off Stanley Robotics

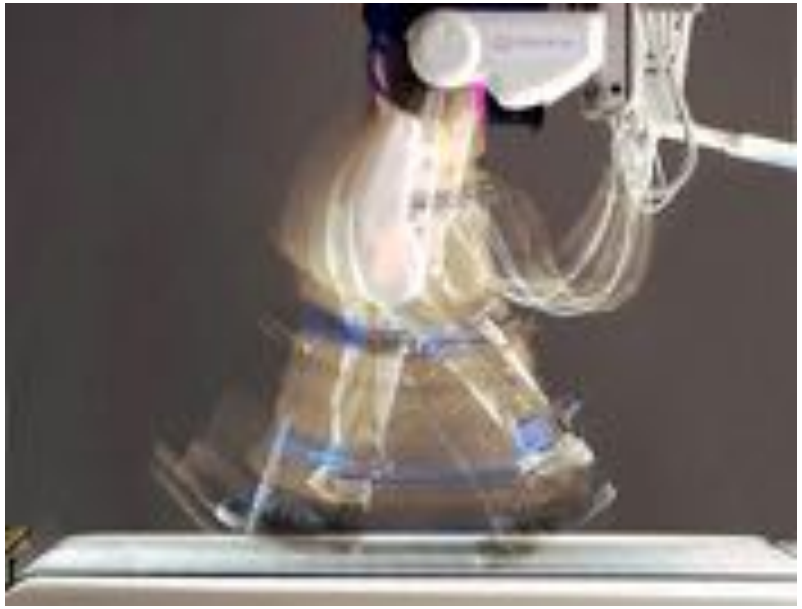
COLLABORATIVE ROBOTS

robot systems for medical interventions

COLLABORATIVE ROBOTS

virtual reality based training systems using haptic interfaces

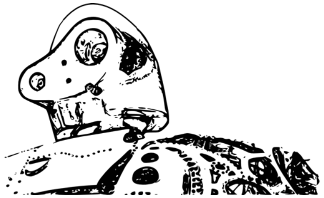
microsurgery training at NUS



Lokomat for walk neuro-rehabilitation @ Hocoma

COLLABORATIVE ROBOTS

- have to smoothly and efficiently interact with human voluntary movements
- should consider the users' safety, neuromechanics and sensorimotor control, in addition to the requirements of the environment



control

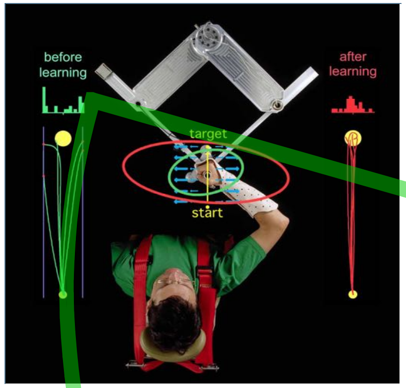
psychology

robotics

neuroscience

physiology

human-machine interaction



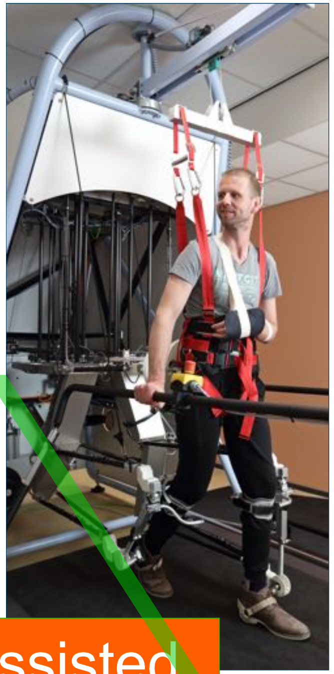
human motor control

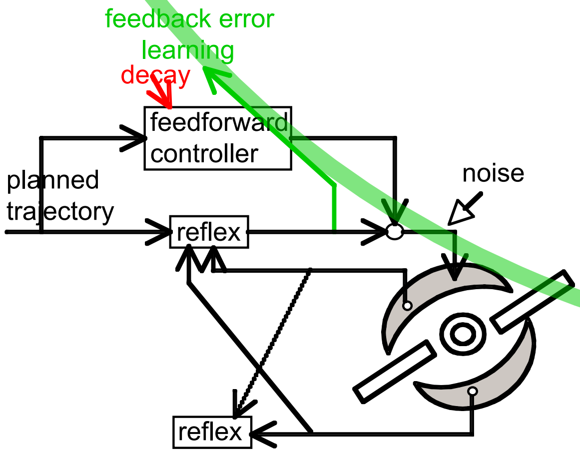
computational neuroscience

assistive devices

virtual reality based surgery training

robot-assisted rehabilitation



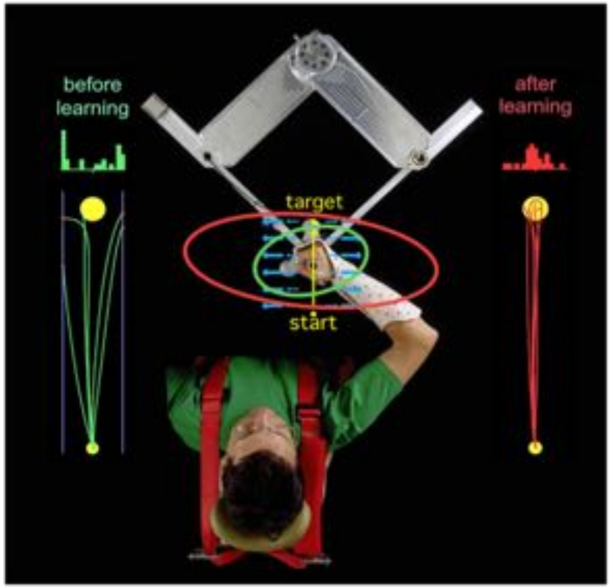


www3.imperial.ac.uk/
humanrobotics

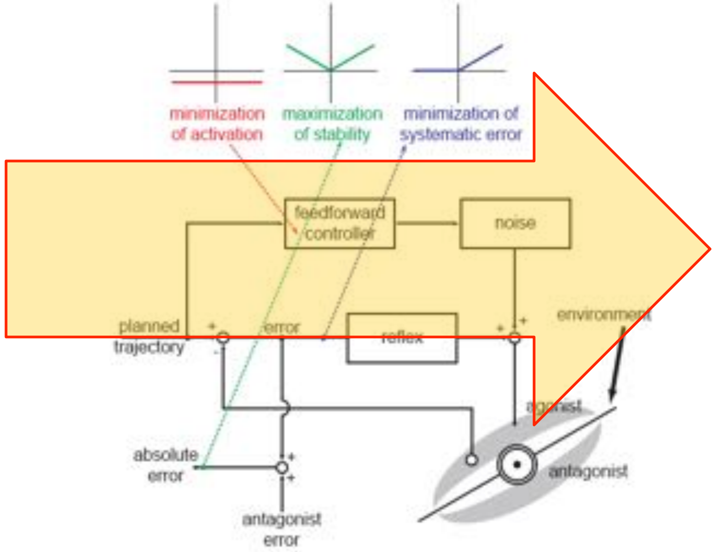
COLLABORATIVE ROBOTS

- motor learning: in humans, for robots
- rehabilitation devices to train the upper limb in neurologically impaired individuals
- dedicated robots to investigate the neural control of movements
- robots for mobility assistance

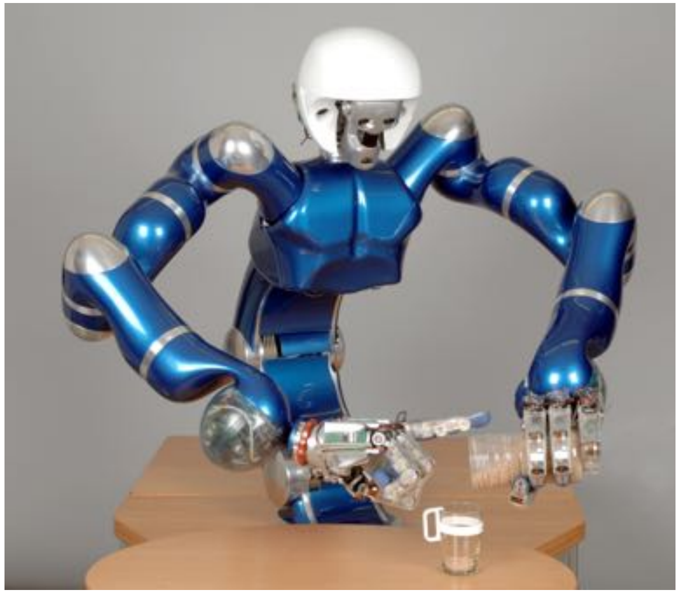
MOTOR LEARNING: in humans, for robot



proof of impedance control in humans
Nature 2001



understanding muscle coordination learning
The Journal of Neuroscience 2008



new strategy to learn optimal interaction control in robots
IEEE Transactions on Robotics 2011 Best Award

HUMAN MOTOR LEARNING

- we constantly need to learn new tasks and adapt to changing conditions, e.g. during infancy or with ageing

- similarities between neuro-rehabilitation and motor learning in healthy subjects as a tool to develop efficient rehabilitation strategies

INTERACTION LEARNING

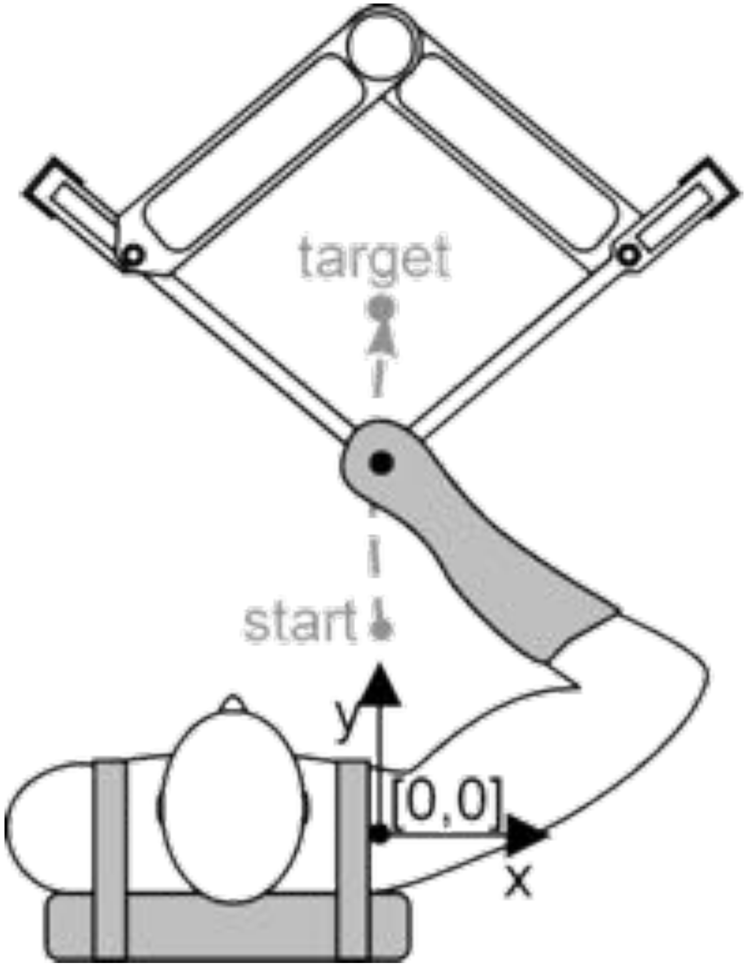
screwdriver

chiseling, carving

- in unstable tasks typical of tool use, sensorimotor noise leads to errors and unpredictability
- this requires to compensate for the interaction force and instability by adapting muscles activity

TO INVESTIGATE INTERACTION LEARNING IN UNSTABLE DYNAMICS

- point to point movements

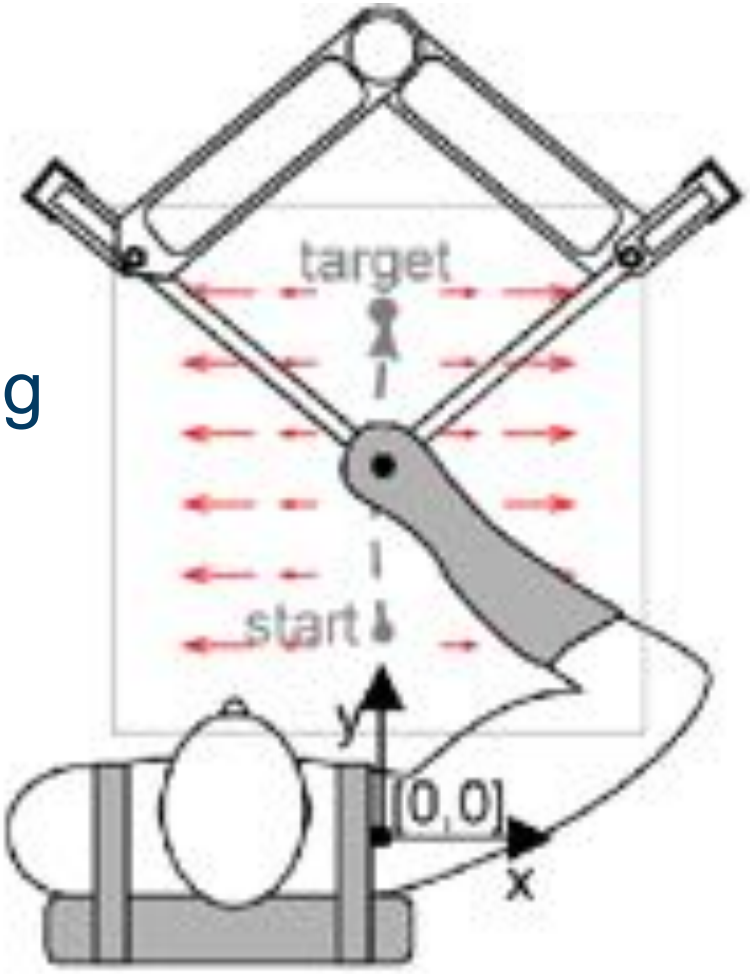


TO INVESTIGATE INTERACTION LEARNING IN UNSTABLE DYNAMICS

- point to point movements

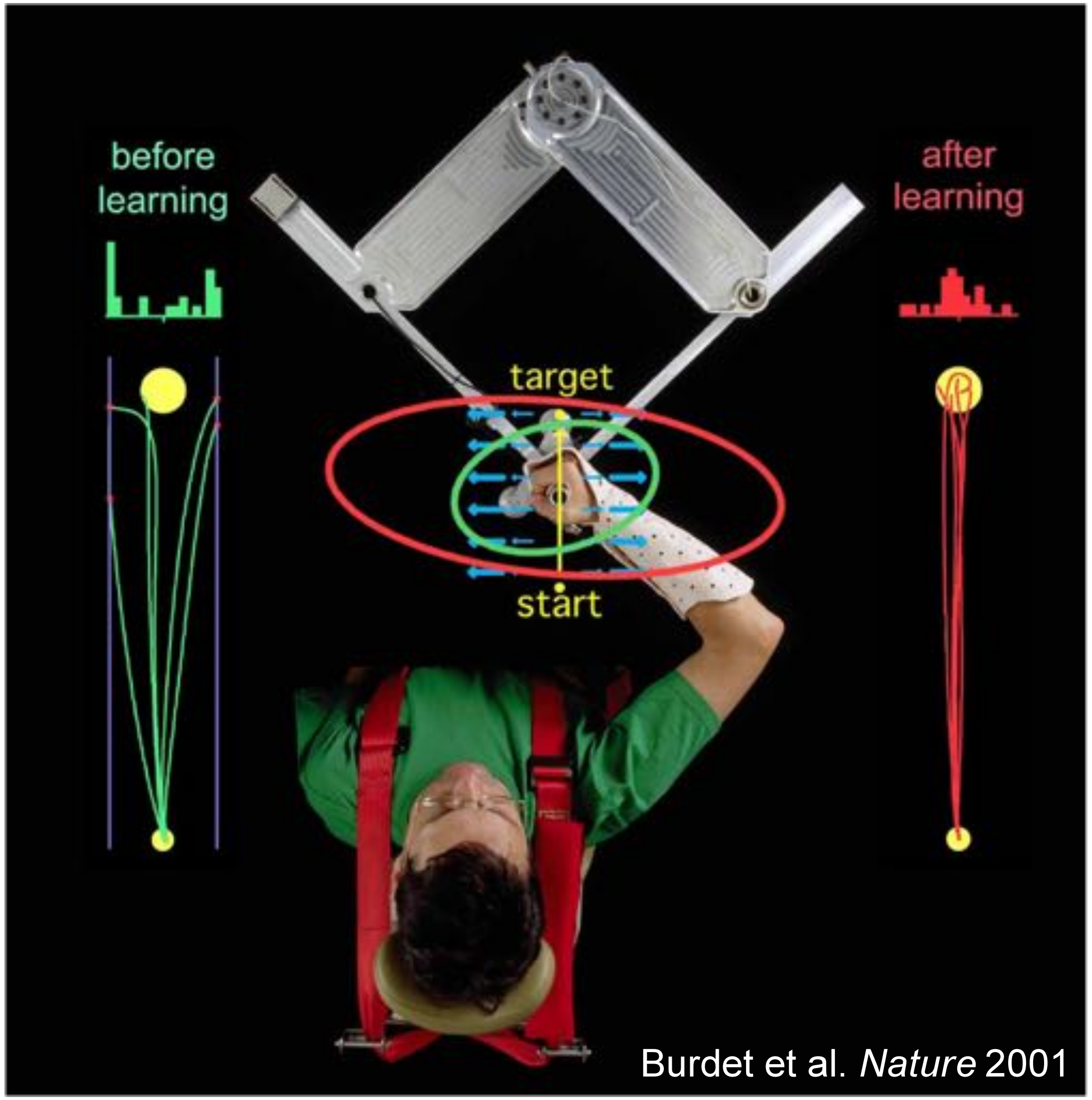
- forces diverting

to left



or to right

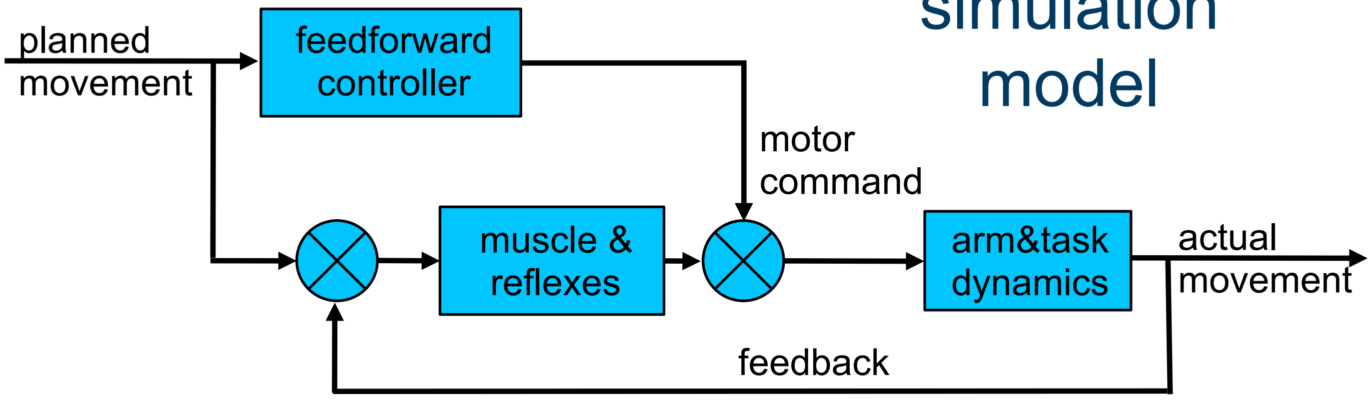
LEARNING INSTABILITY TYPICAL OF TOOL USE



Burdet et al. *Nature* 2001

- the nervous system reorganises muscles activity through learning
- feedforward force compensates for the interaction with the environment
- stiffness increases to counteract the instability

LEARNING MODEL



planned movement

feedforward controller

motor command

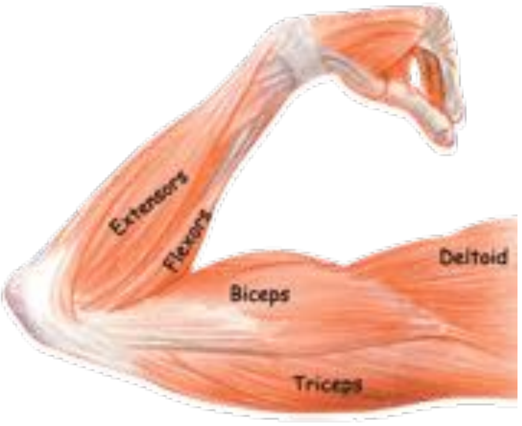
muscle & reflexes

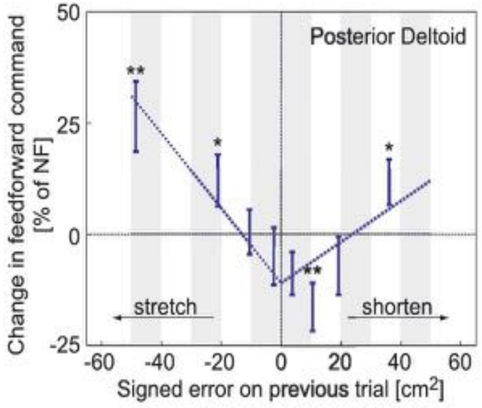
arm&task dynamics

actual movement

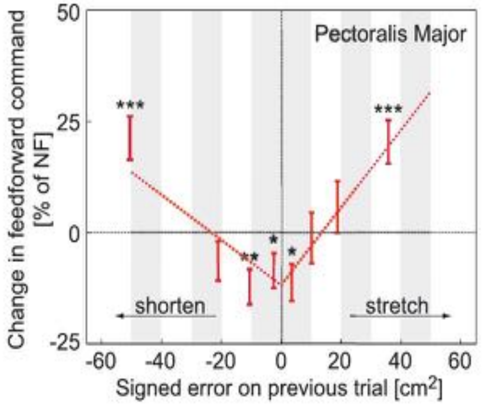
feedback

simulation model





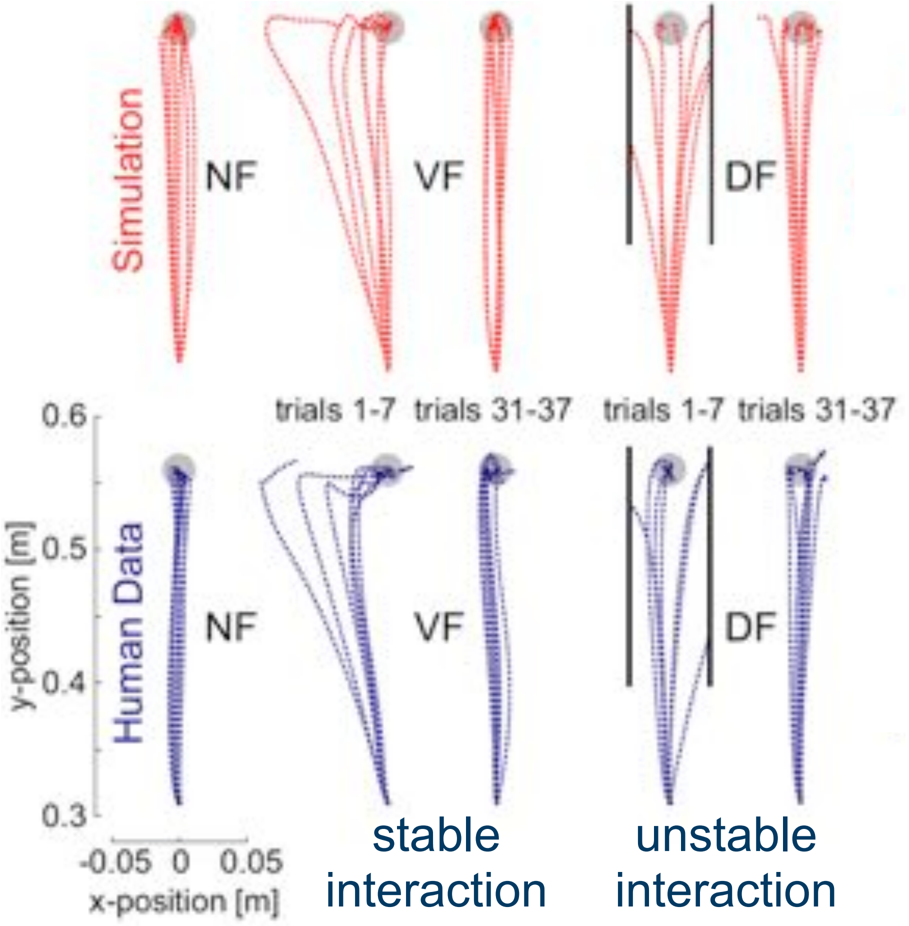
change of muscle activation



[Franklin et al. 2008 J Neuroscience]

LEARNING MODEL

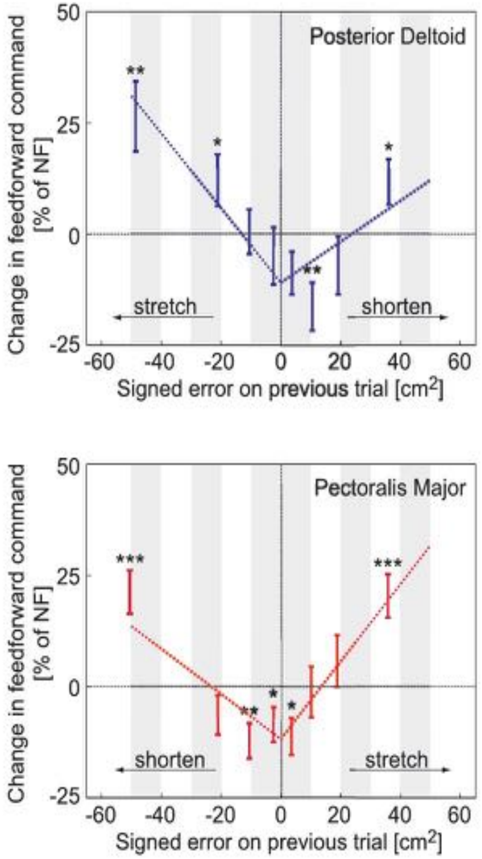
minimisation of error & effort in muscles predicts the learning observed in experiments



stable interaction

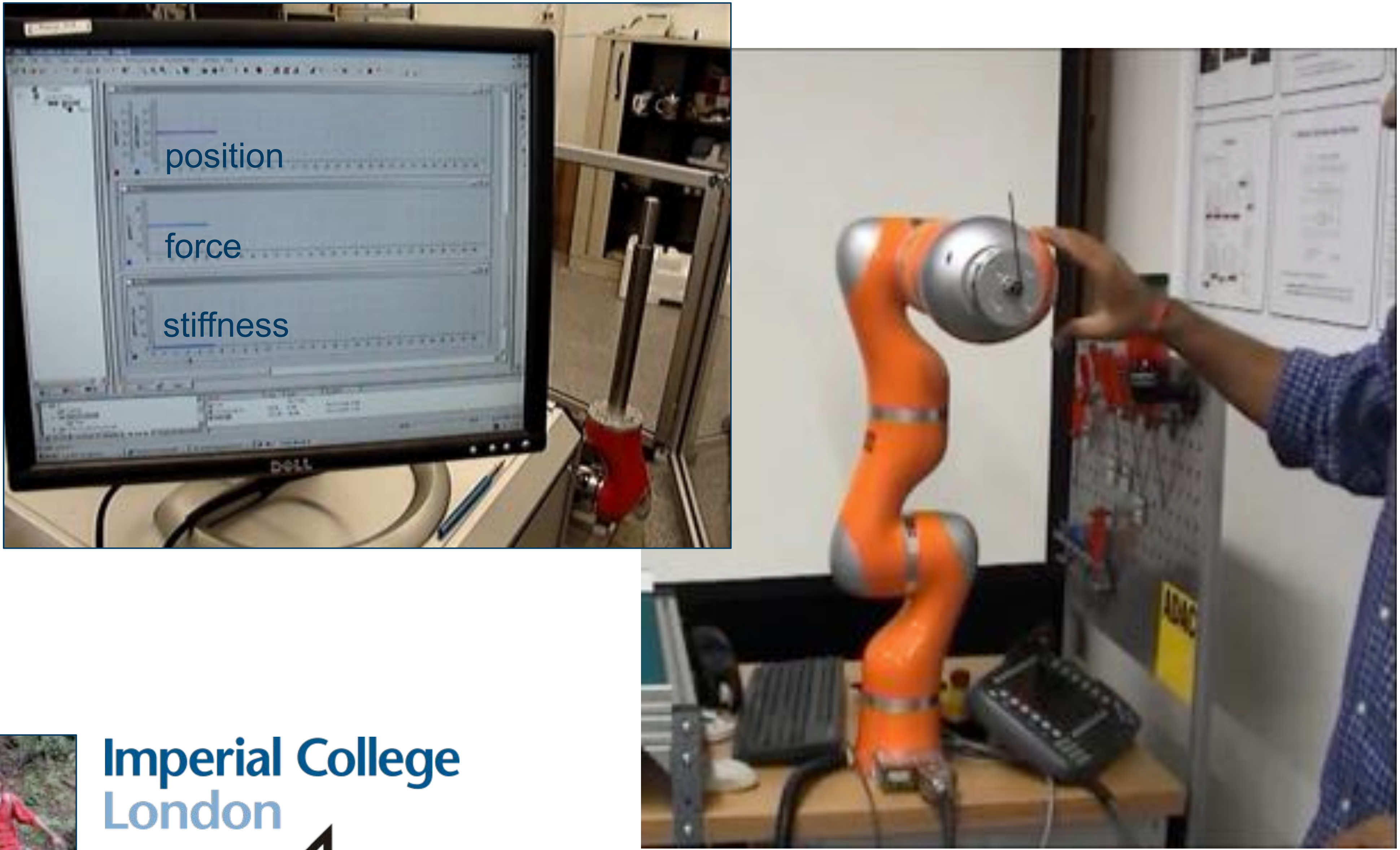
unstable interaction

change of muscle activation



[Franklin et al. 2008 J Neuroscience]

LEARNING: FROM HUMAN TO ROBOT



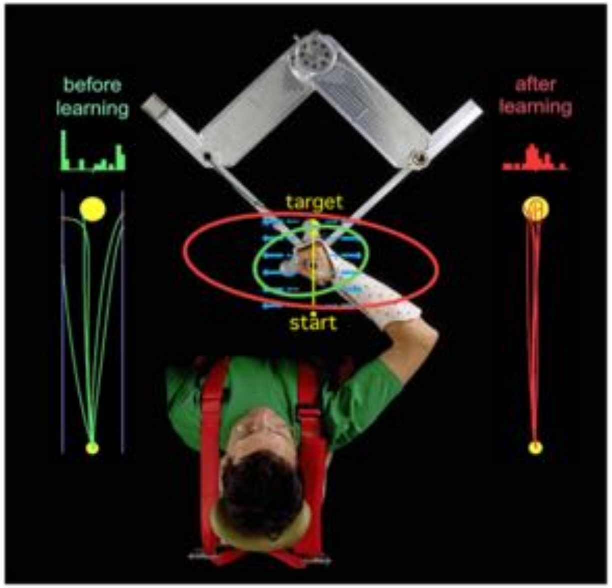

Ganesh Gowrishankar

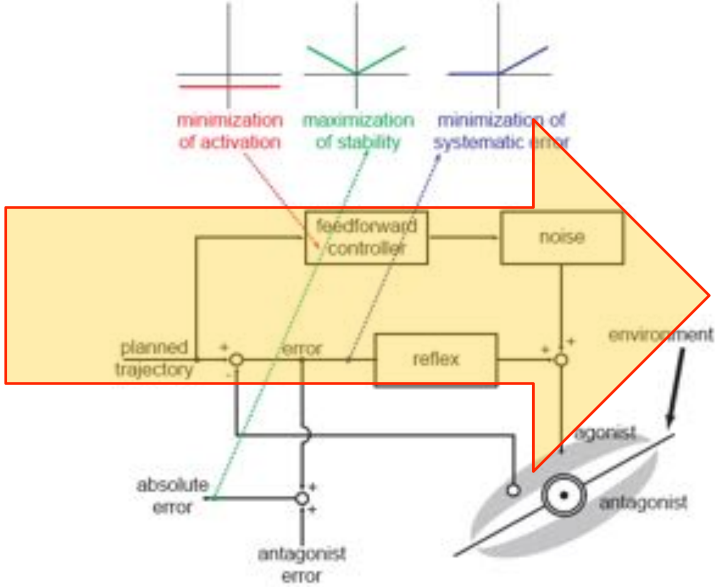
Imperial College London

DLR

[Yang, Ganesh et al. 2011 IEEE Transactions on Robotics]

- Our model of motor learning can be used to predict and study the neural control of movement and posture
- in humans, interaction is continuously adapted to minimise error and effort
- human-like guidance adaptation on rehabilitation robots: when the patient is improving, robot assistance will relax





[Burdet et al.: J of Neuroscience 2008, IEEE Trans on Robotics 2011, PLoS ONE 2012]

COLLABORATIVE ROBOTS

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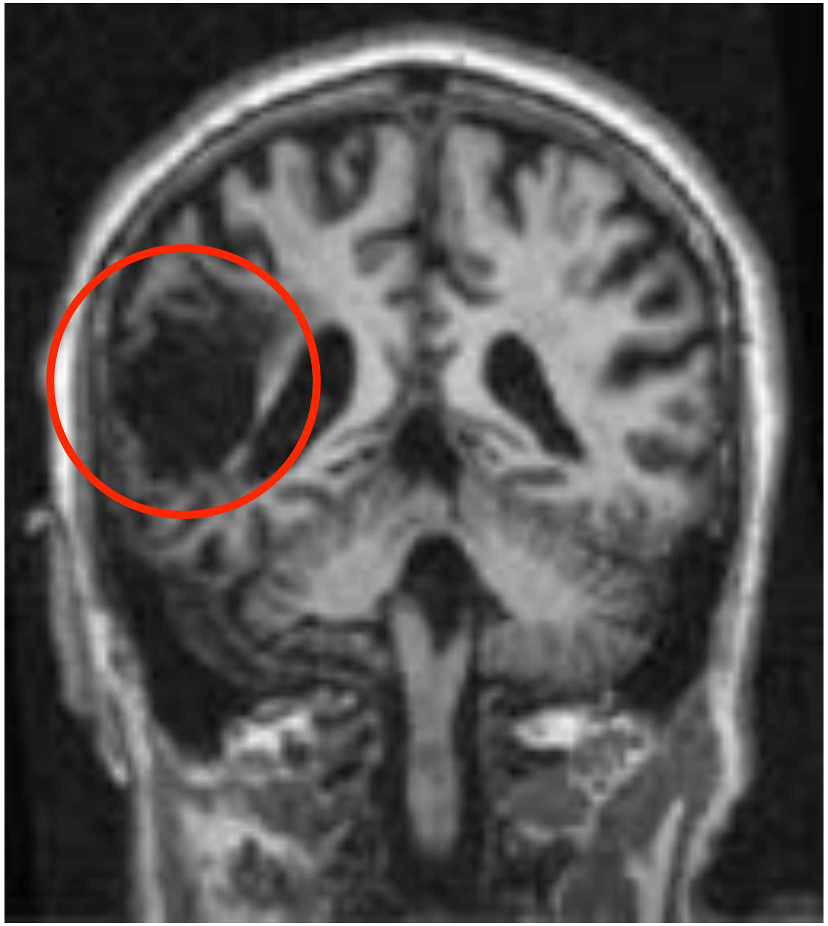
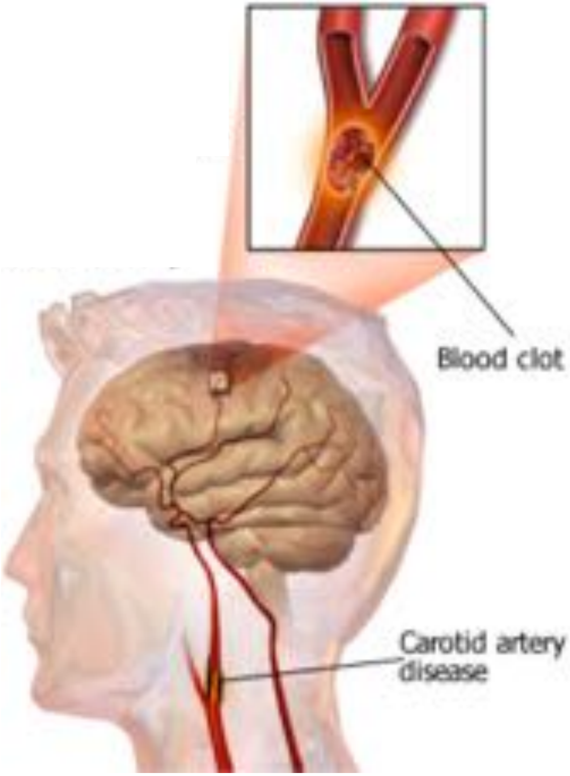
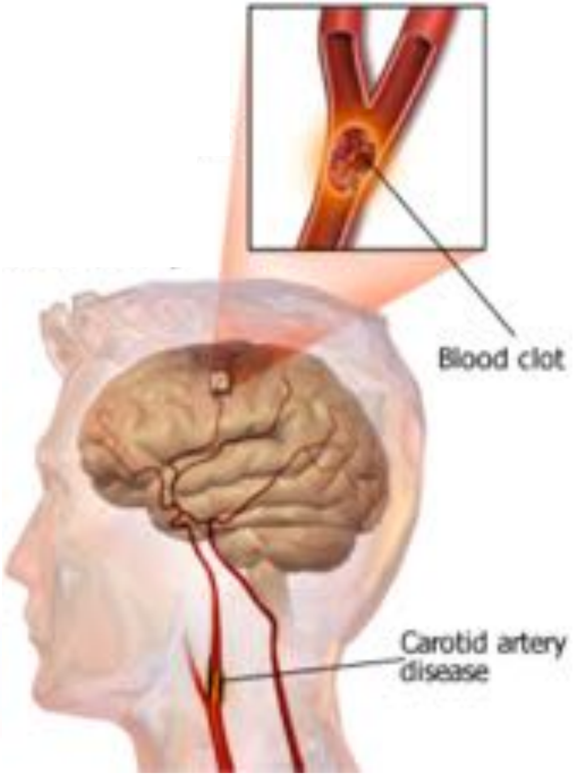
STROKE





a part of the brain does not receive enough oxygen, e.g. due to a clot in a cerebral artery

TYPICAL POST-STROKE REHABILITATION IN THE UK



24 hours

Stroke

↓

Acute Brain Injury Unit (ABIU)

↓

6 - 12 weeks

Rehabilitation (2 sessions PT and 1 session OT)

45 minutes each session 5 days/week

↙ ↘

60 %

Go home if can walk

40 %

Stay on for four months

ROBOT-ASSISTED NEUROREHABILITATION

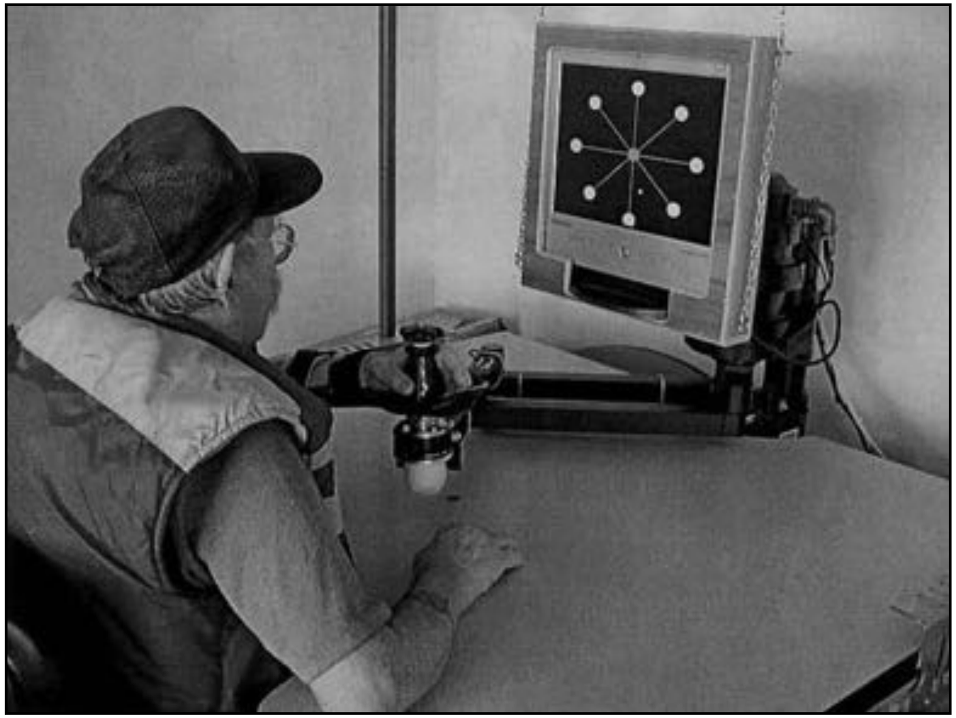
- number of individuals with motor impairments due to neurological diseases is increasing

- patients with neurological disease receive too little therapy for optimal motor recovery

THE NATIONAL HOSPITAL FOR NEUROLOGY AND NEUROSURGERY

- robotic devices can provide motivation through games, control training and objectively measure performance

REHABILITATION OF ARM FUNCTION



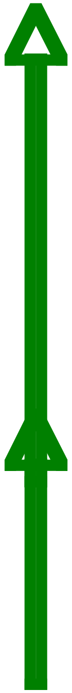
MIT-Manus to train horizontal arm movements

- information from position, velocity and torque sensors
- assistive/resistive load

MIME (Stanford U) to train arm movements in space

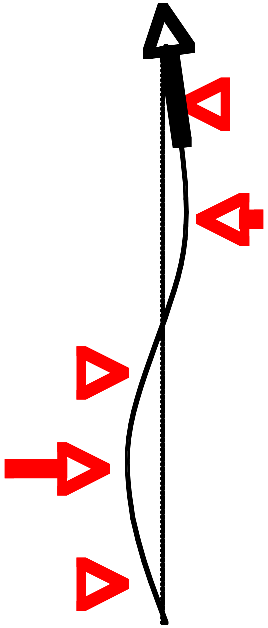
- possibility of teaching mirror movements using the unaffected limb

PASSIVE CONTROL MODALITY



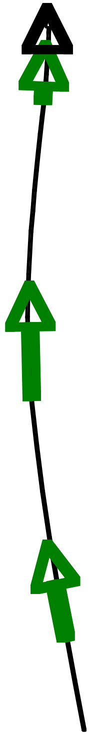
- provides patient with proprioceptive sensory feedback without active muscle fibers or motoneuron activity
- can be used to stretch muscles to increase passive range of motion

GUIDED CONTROL

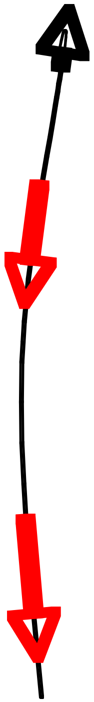


- provides patient with proprioceptive sensory feedback of errors in force direction
- prevents patient from making hand path errors but does not correct muscle activation patterns

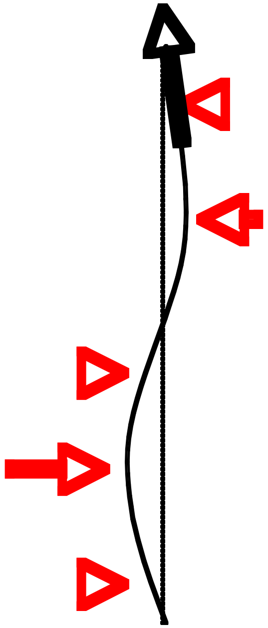
ACTIVE CONTROL



- provide normal proprioceptive feedback during movement
- assistive force allows patients to increase speed or complete difficult movements
- resistive force helps increase strength



ERROR AUGMENTATION



- provides increased (proprioceptive) sensory feedback of errors
- force the patient to correct muscle activation patterns

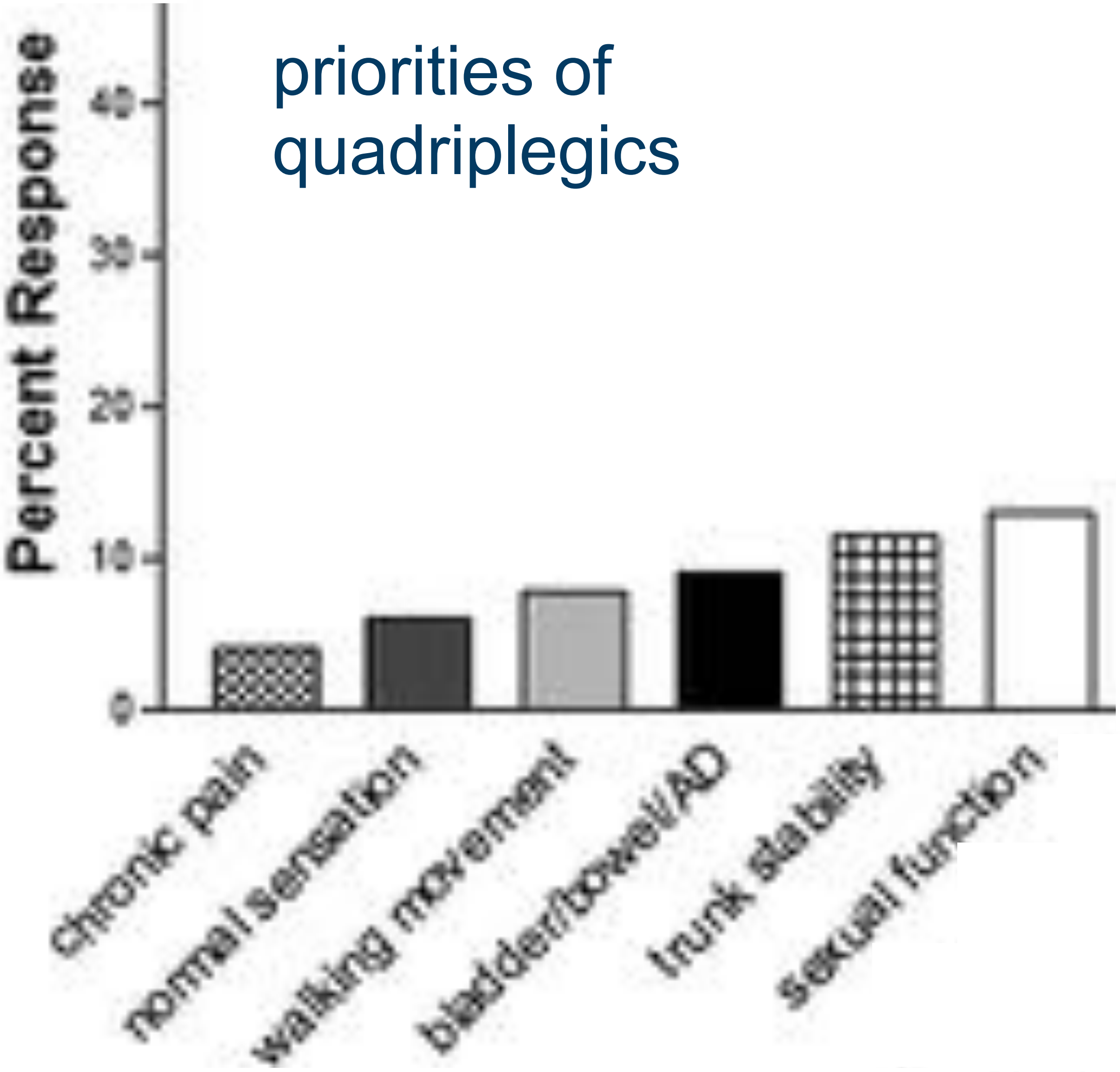
RESULTS OF CLINICAL TRIALS

Hocoma

- robot-assisted therapy is as effective as conventional therapy
- clinical improvements following intensive robot-assisted therapy of chronic patients are statistically significant but small
- passive movement is insufficient, active participation is required
- training planar movements does not transfer well to functional tasks, e.g. manipulation

[see Hogan et al. JRRD 2006; Kahn et al. JRRD 2006]

IMPORTANCE OF HAND FUNCTION



priorities of quadriplegics

[Anderson J Neurotrauma 2004]

ARM ROBOTS WITH HAND MODULE

THZ)

d

me

ke

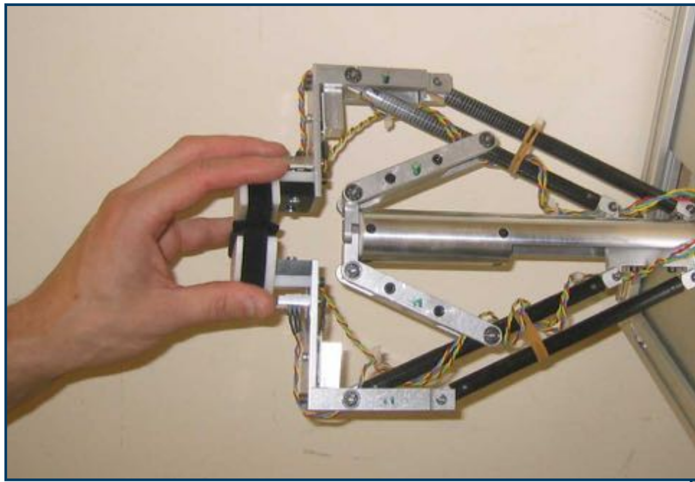
Gentle (U Reading)

FIND OUT FUNCTIONS THAT STROKE PATIENTS MISS MOST

- knob manipulation
  (to operate ovens, washing machine etc.)
- handwriting
- driving
- card playing, cutting nails and similar fine manipulation

OUR COMPACT ROBOTS TO TRAIN HAND FUNCTION

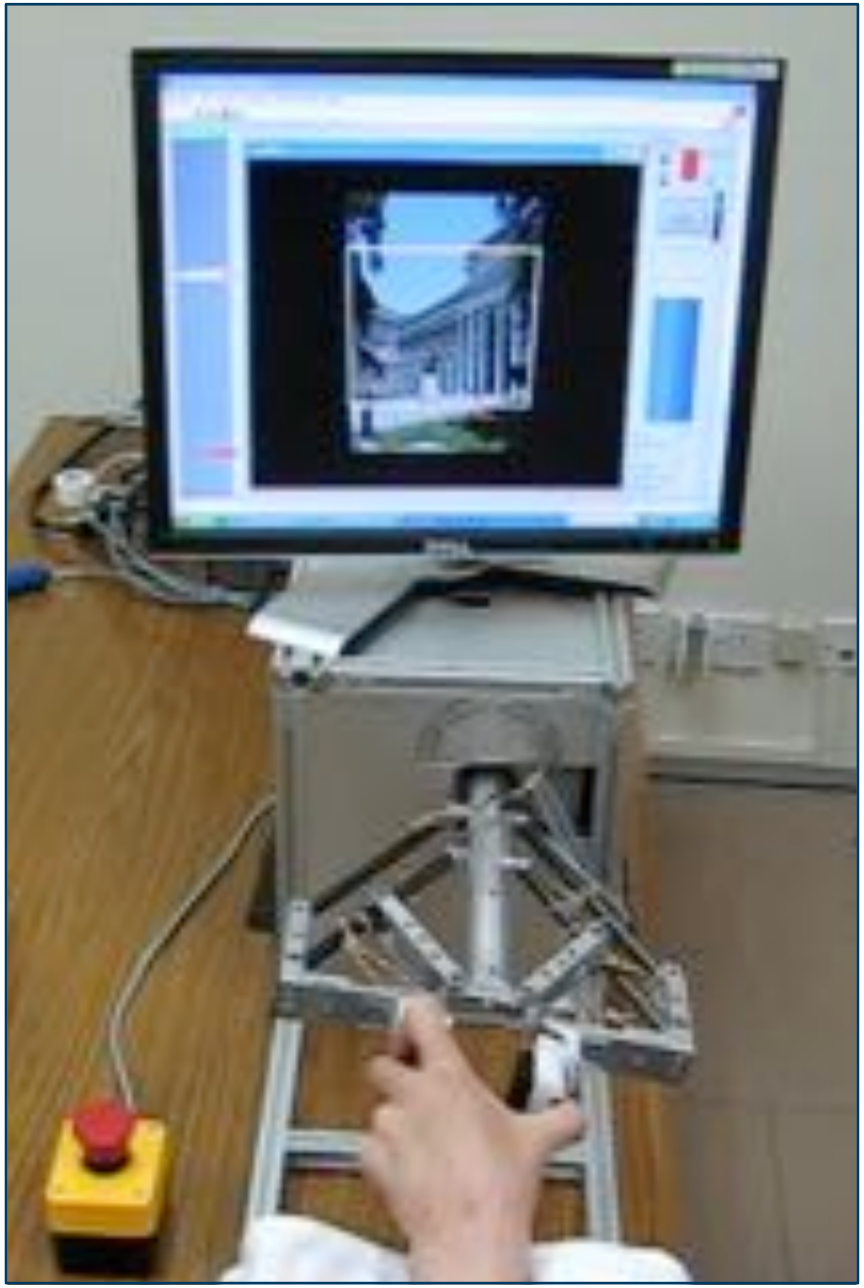
HandCARE
finger coordination
and independence,
tactile sensation



Haptic Knob
hand opening,
knob manipulation
and grasping

[Lambercy, Dovat et al. IEEE Transactions on Neural Systems and Rehabilitation Engineering 2007, 2008]

HAPTIC KNOB: OPENING/CLOSING GAME

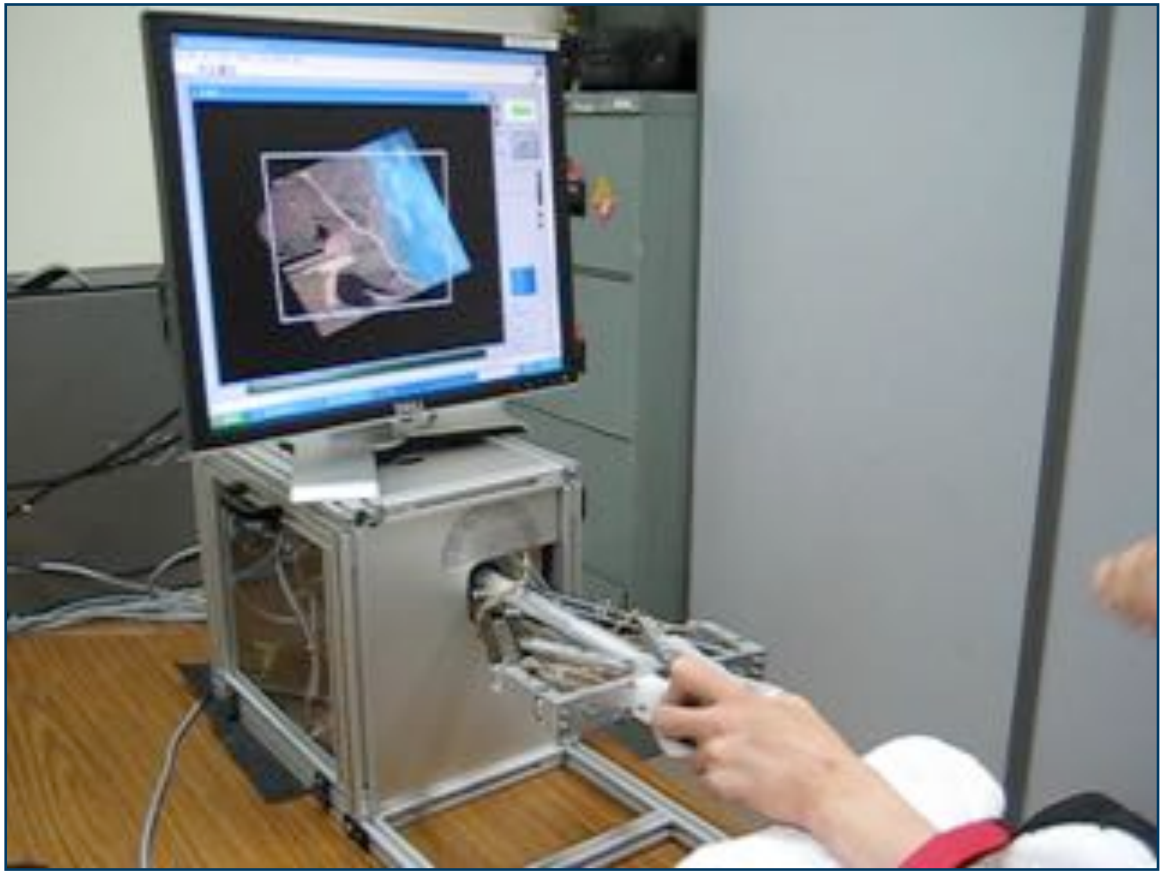


- passive opening to train finger extension
- training slow grasping along a smooth trajectory
- automatic increase of difficulty (slow movement) with performance

Tan Tock Seng HOSPITAL

[Lambercy et al. 2011 Journal of NeuroEngineering & Rehabilitation]

HAPTIC KNOB: PRONOSUPINATION GAME



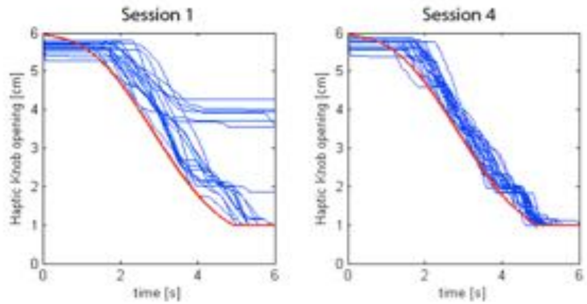
- score = *f*(*adjustment time*)
- automatic adaptation of difficulty level with increase of resistance and required precision

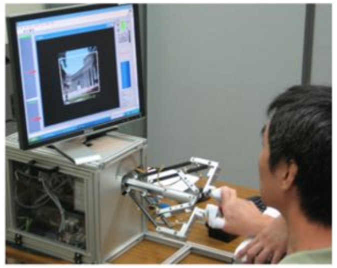
Tan Tock Seng HOSPITAL

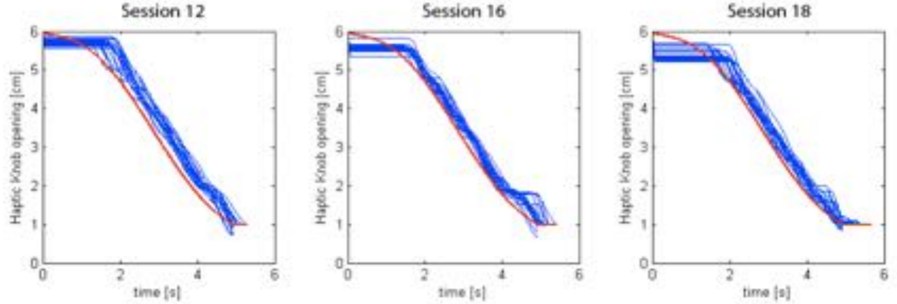
[Lambercy et al. 2011 Journal of NeuroEngineering & Rehabilitation]

HAPTIC KNOB: CHRONIC PATIENTS TRIAL

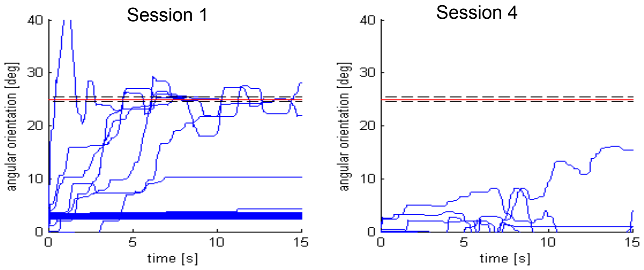
hand closing

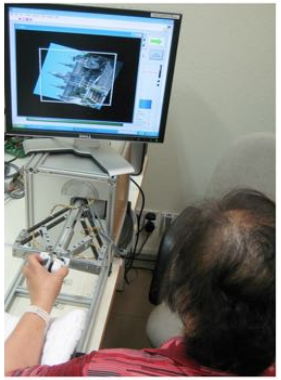


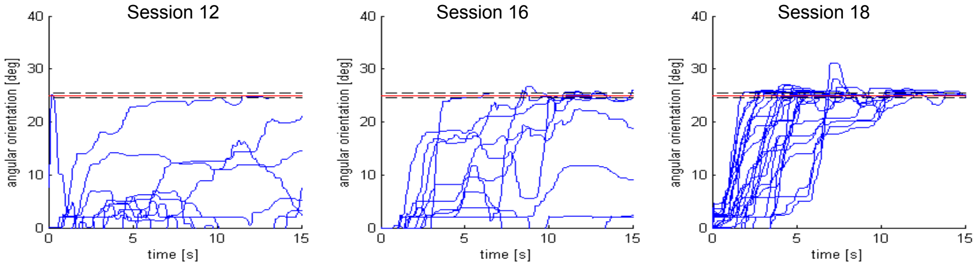




forearm rotation







- therapists found an improvement of hand *and* arm functions

- this suggests that compact hand robots offer an alternative to large exoskeleton arm robots

Tan Tock Seng
HOSPITAL

[Lambercy et al. 2011 Journal of NeuroEngineering & Rehabilitation]

WHICH ROBOT FOR REHABILITATION?

rehabilitation objects

<100£

passive sensor-based systems

100£-5000£

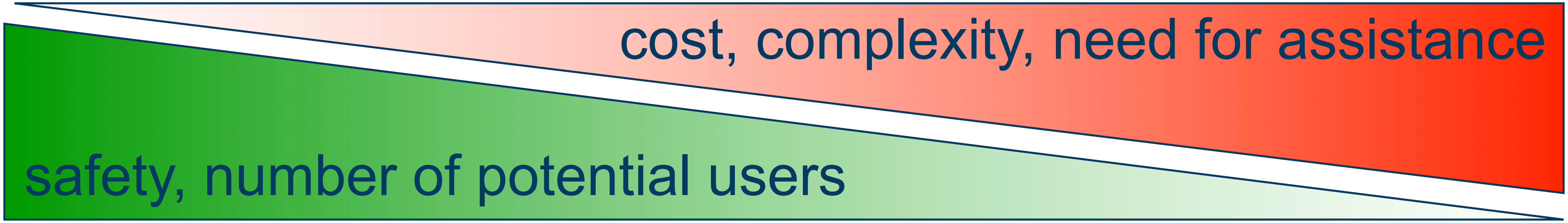
simple robots for decentralised use

~10’000£

complex robots

100’000-1’000’000£

Human
Robotics



cost, complexity, need for assistance

safety, number of potential users

SITAR system for independent task-oriented assessment and rehabilitation

- a table workbench
- low-cost force touch screen & intelligent objects
- sensors to infer patient's behaviour
- assessment with partners in London (UCL, Imperial), UPMC Paris, CMC Vellore (India)

Imperial College
London


Asif Hussain


Nathanael Jarrassé


Nick Roach


Julius Klein


Sivakumar Balasubramanian

tyromotion

FOR REHABILITATION

MYRO®

- interactive therapy device, for one of multiple players
- immersive, with natural visuo-motor coordination
- detection of multi-touch and interaction force
- for manipulation with real objects or graphomotor tasks
- ideal for task-oriented training
- audio feedback

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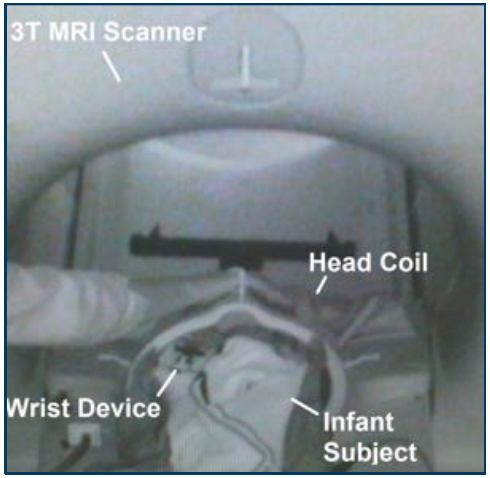
SENSORI-MOTOR ACTIVITY IN PRETERM INFANTS

- up to 10% of babies born prematurely will develop cerebral palsy
- detect abnormal brain activity using functional magnetic resonance imaging (fMRI) and a compatible robot
- (re)habilitation



Imperial College Healthcare NHS
NHS Trust

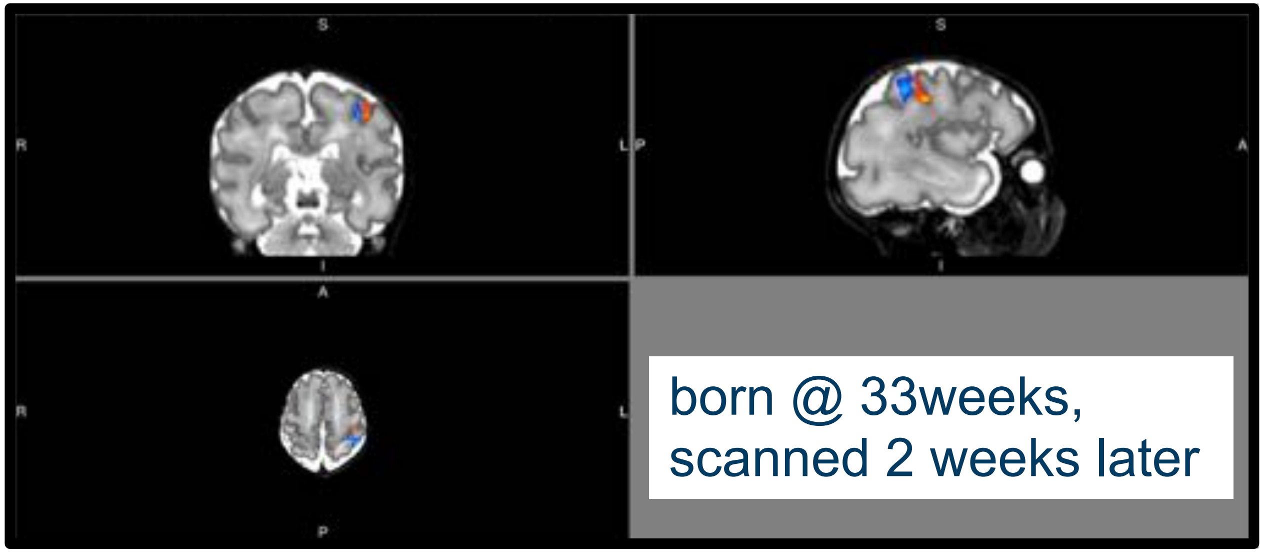
Guy's and St Thomas' NHS
NHS Foundation Trust

SENSORI-MOTOR ACTIVITY IN PRETERM INFANTS

- tiny pneumatic wrist robot
- sensing through optical fibre
- passive movement (robot moves)
- premature infants make infrequent spontaneous movements

passive movement yields activity in the contralateral primary sensory cortex

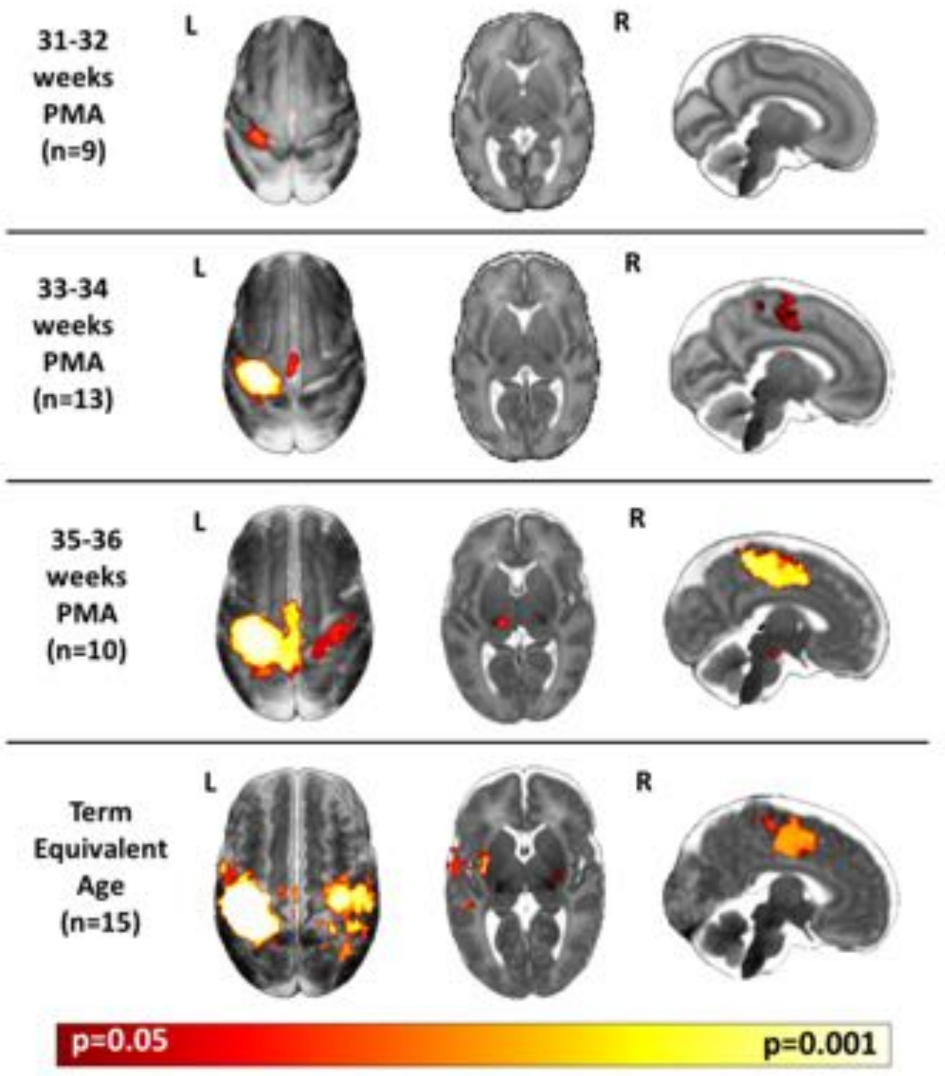
active results cluster in primary motor cortex



born @ 33weeks, scanned 2 weeks later

[Allievi et al. 2013 IEEE T. Biomedical Engineering]

SENSORY ACTIVITY FROM PRETERM BIRTH TO AGE CORRECTED BIRTH



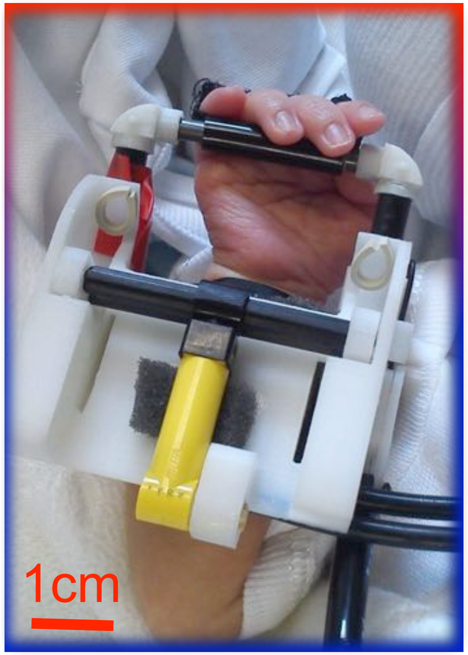
↑ complexity of functional responses

↑ involvement of accessory areas and ipsilateral hemisphere

overall response decreases at term

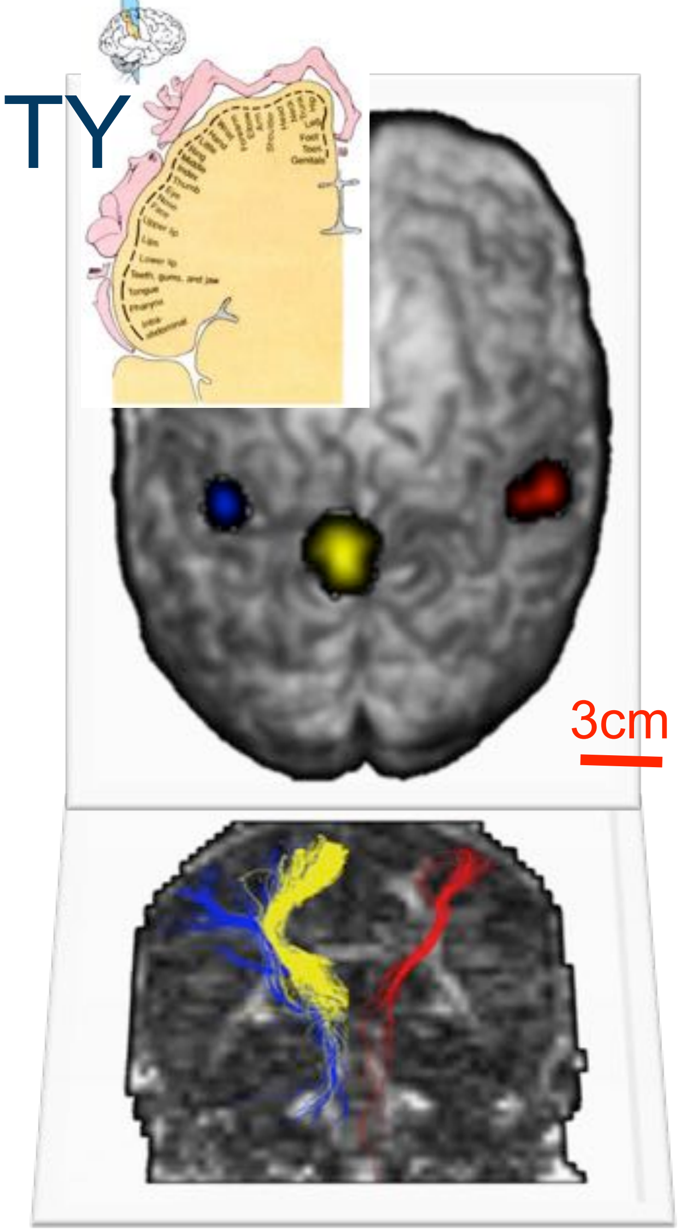
[Allievi et al. 2015 Cerebral Cortex]

SENSORI-MOTOR ACTIVITY IN PRETERM INFANTS



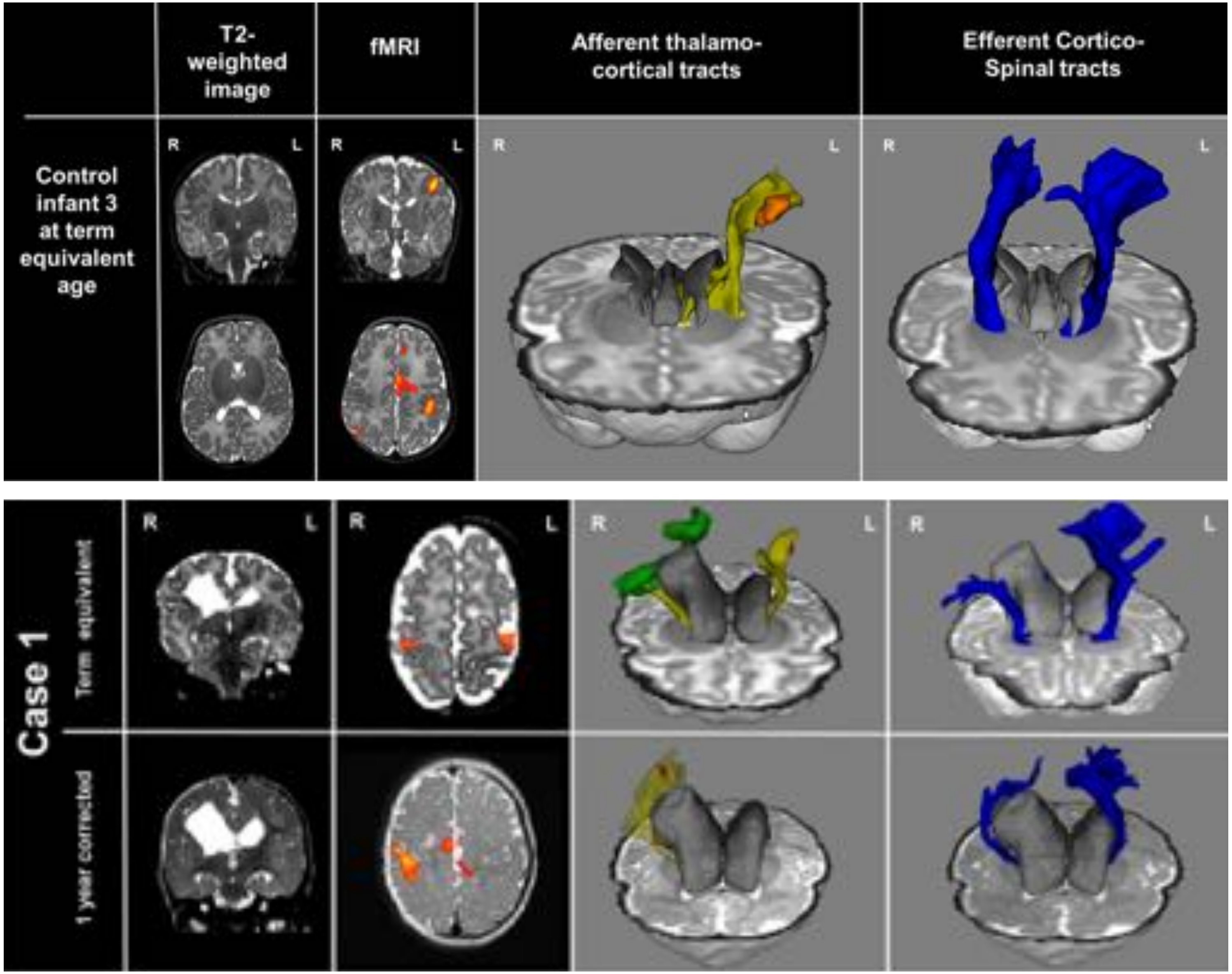
right/left wrist interface

right ankle interface



using wrist and ankle interface, we can precisely characterise the somatosensory map in infants, which is similar to the adult homunculus

STRUCTURAL AND FUNCTIONAL CONNECTIVITY IN STROKE INFANT



control preterm infant

preterm infant with stroke

[Arichi et al. 2014 Neuroradiology]

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KINEASSIST @ KINEADESIGN

Standing on foam surface.

Being supported and after losing balance.

- let the patient in charge of the movement
- allows therapists to safely challenge patients in functional environments with minimal effort

NEED FOR IMPROVED POWER WHEELCHAIR MOBILITY

- of the 1.7 million adults who use wheeled mobility devices in USA, only 9.1% use motorised wheelchairs (Kaye 2000)
- clinical survey (Fehr 2000) revealed that for patients who receive power wheelchair training:
  - 9~10% find it extremely difficult or impossible to use the wheelchair for daily activities
  - 40% find it difficult or impossible to manoeuvre the wheelchair

COLLABORATIVE WHEELCHAIR

help the disabled by:

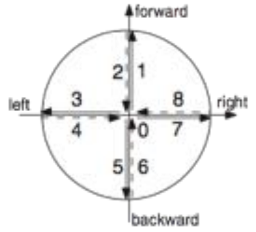
- relying as much as possible on her or him
- providing guidance along paths defined in software
- allowing them to vary the level of autonomy to suit their ability

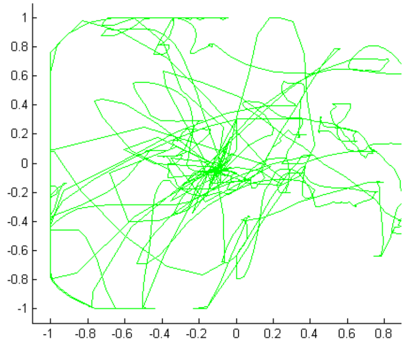
NUS National University of Singapore

Imperial College London

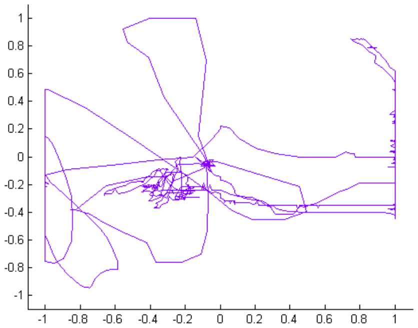
[Zeng et al. IEEE TNSRE 2008, Disability and Rehabilitation 2009]

SUBJECT A

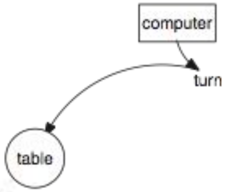


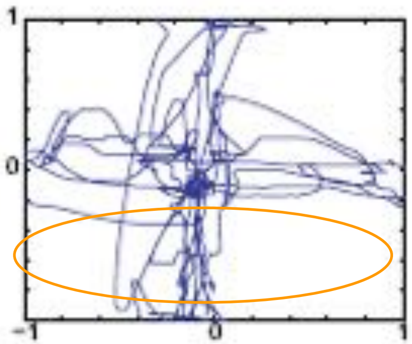


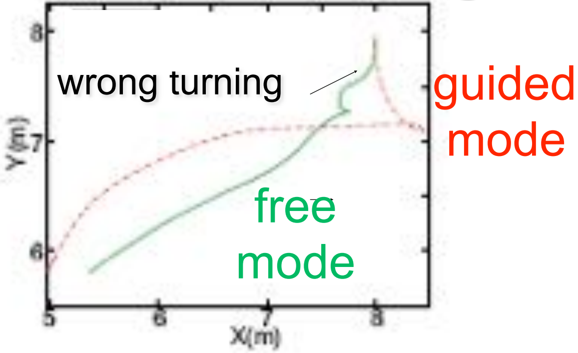
joystick input without guidance



joystick input with guidance



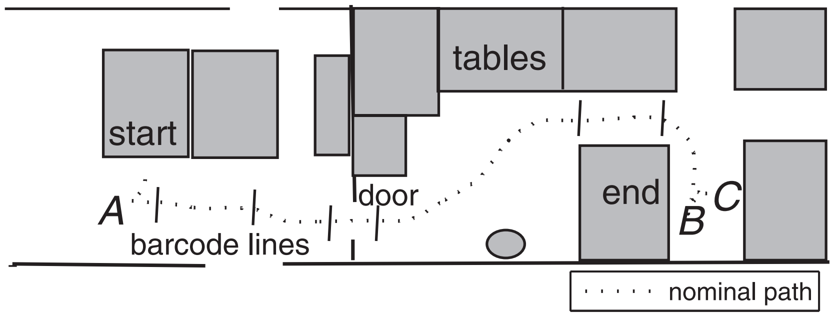




- 26y cerebral palsy
- good understanding but cannot talk clearly
- wide oscillations in the arms
- can only use a manual chair, pushing backward with feet

[Zeng et al. 2009 Neurorehabilitation & Neural Repair]

NAVIGATION TEST



collisions happened with conventional WC for every subject, but no collision with collaborative WC

conventional wheelchair

collaborative wheelchair

[Zeng et al. 2009 Neurorehabilitation & Neural Repair]

ADAPTIVE PATH GUIDANCE

- human-robot collaboration motto: “from each according to his ability, to each according to his needs”
  - human: planning, speed control including start/stop
  - machine: assist in manoeuvring by constraining motion along guide paths

- neither complex sensor processing nor a decision system is required: simple and safe robotic system

COLLABORATIVE ROBOTS FOR MOBILITY ASSISTANCE AND REHABILITATION

- do not impose a robotics solution
- experiments with healthy and impaired end users
- major issue: human-machine interaction
- let the impaired users (as much as possible) in charge of the control
- we often come to interesting and challenging robotics problems

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