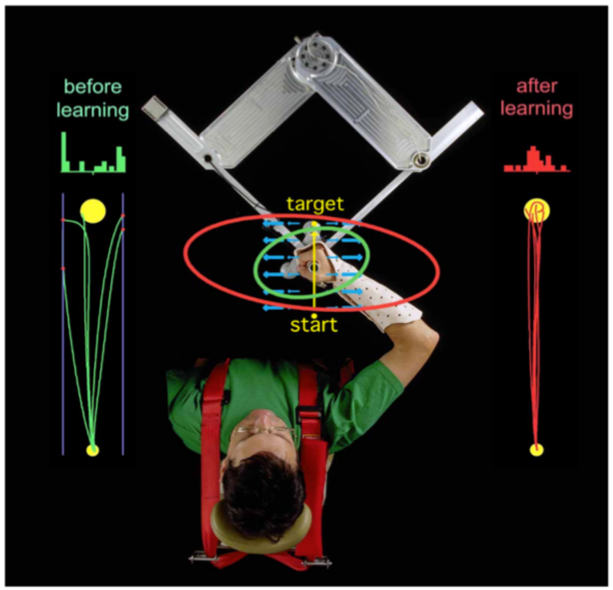
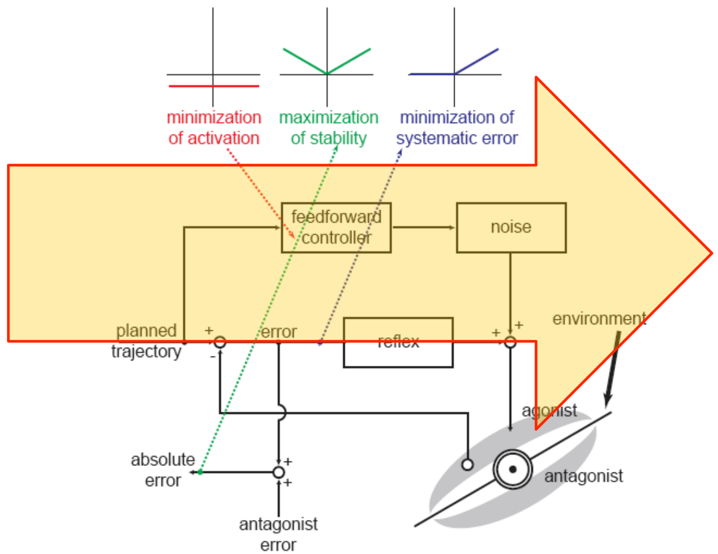
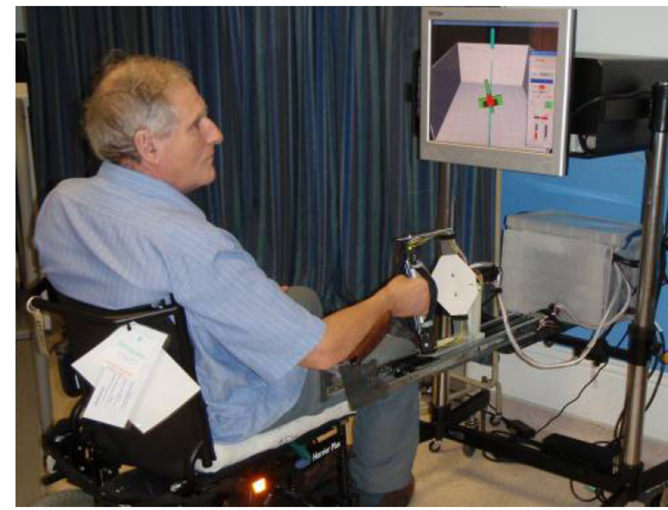
HUMAN ROBOTICS

- muscle mechanics and control
- single-joint neuromechanics
- multi-joint multi-muscle kinematics
- multi-joint dynamics and control
- motor learning and memory
- interaction control
- motion planning and online control
- integration and control of sensory feedback
- applications in neurorehabilitation and robotics

Robot-assisted, neuroscience-based rehabilitation&assistance







Etienne Burdet

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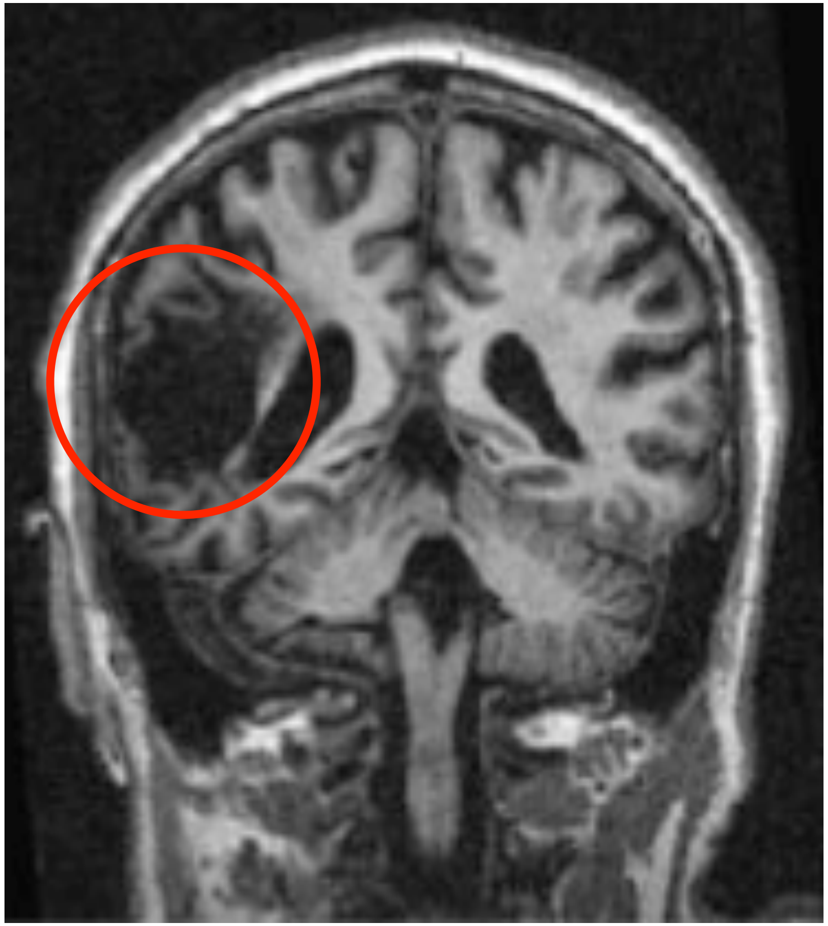
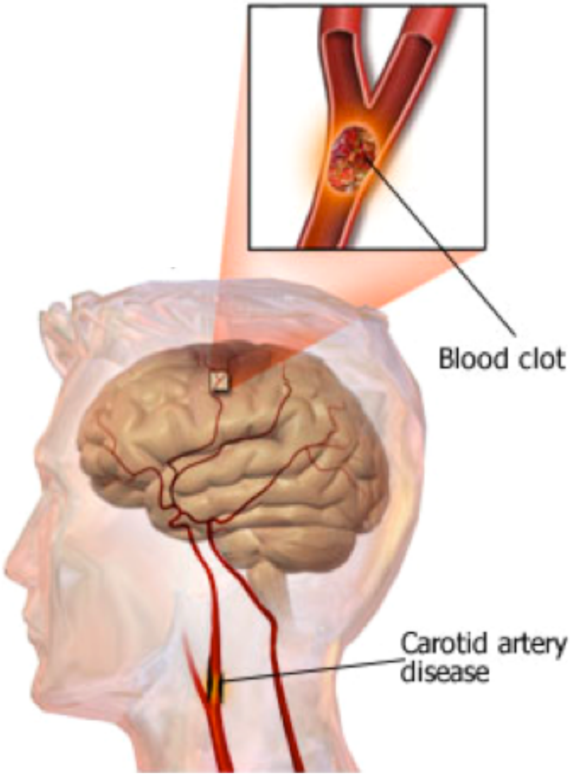
Imperial College London

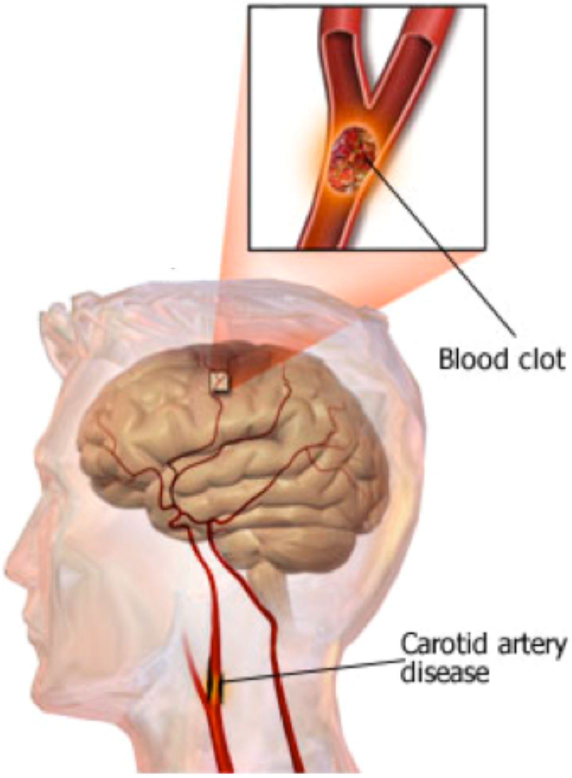
STROKE





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 %	**40 %**
Go home if can walk	**Stay on for four months**

NATIONAL HOSPITAL FOR NEUROLOGY AND NEUROSURGERY, LONDON

rehabilitation for reaching

sensibilization

IMPORTANCE OF NEUROREHABILITATION

- number of individuals with motor impairments due to neurological diseases (e.g. stroke, Parkinson’s disease, cerebral palsy, spinal cord injury) is increasing
- patients with neurological disease receive little therapy as resources lack
- studies suggest that more therapy is better, e.g. constraint-induced therapy

MOTIVATION FOR ROBOT-ASSISTED THERAPY

- injured motor system (neural circuits) can reorganize *with extensive training*
- robotic devices can precisely control training and accurately measure performance
- virtual reality workstations can implement motivating therapeutic games
- optimal training techniques (for speed and extent of recovery) are not known

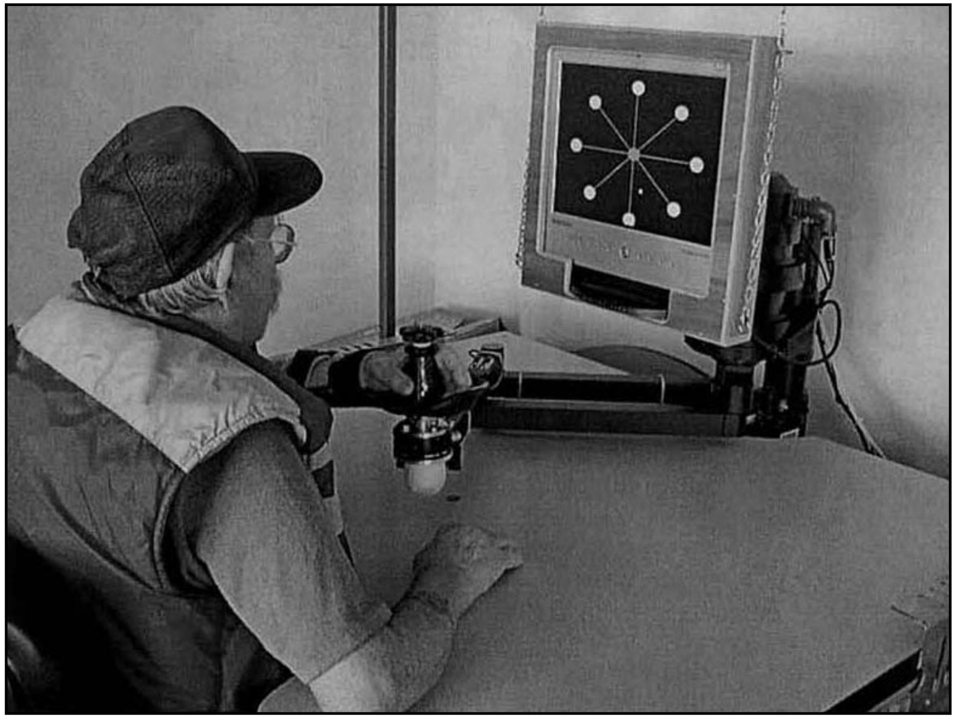
KINEASSIST @ KINEADESIGN

Standing on foam surface.

Being supported and after losing balance.

allows therapists to safely challenge patients in functional environments with minimal effort

REHABILITATION OF ARM FUNCTION



MIT-Manus to train horizontal arm movements

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

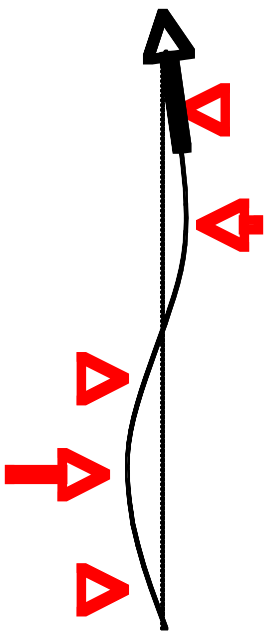
MIME (Stanford U) to train arm movements in space

- possibility of teaching mirror movements using the unaffected limb

PASSIVE CONTROL MODALITY

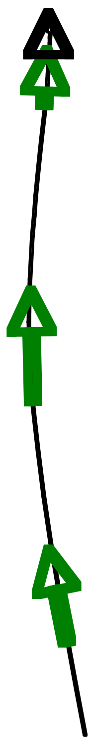
- provides patient with proprioceptive sensory feedback without active muscle fibers or motoneuron activity
- can be used to stretch muscles to increase passive range of motion
- can be implemented with Manus and MIME

GUIDED CONTROL

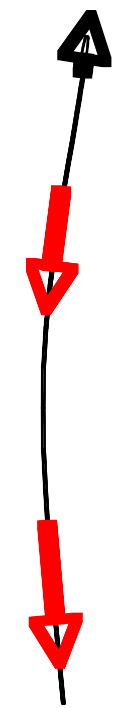


- provides patient with proprioceptive sensory feedback of errors in force direction
- prevents patient from making hand path errors but does not correct muscle activation patterns
- can be implemented on Manus and MIME

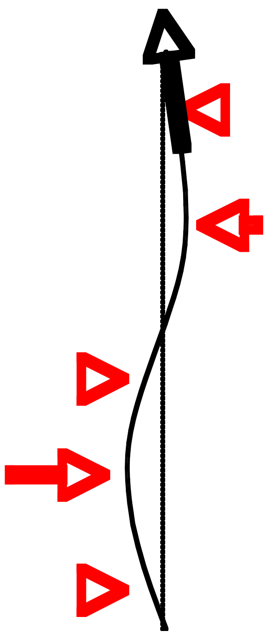
ACTIVE CONTROL



- provide normal proprioceptive feedback during movement
- assistive force allows patients to increase speed or complete difficult movements
- resistive force helps increase strength
- can be implemented on Manus and MIME

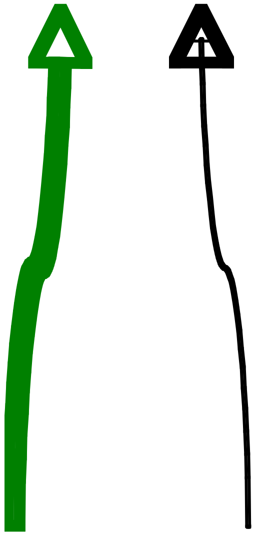


ERROR AUGMENTATION



- provides increased (proprioceptive) sensory feedback of errors
- force the patient to correct muscle activation patterns
- can be implemented on Manus and MIME

MIRROR-IMAGE MODALITY



- unimpaired limb motion to “teach” impaired limb
- provides means to compare sensory feedback from active (unimpaired arm) and passive (impaired arm)
- can only be implemented on MIME

REHABILITATION OF ARM FUNCTION
RESULTS OF CLINICAL TRIALS

- 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]

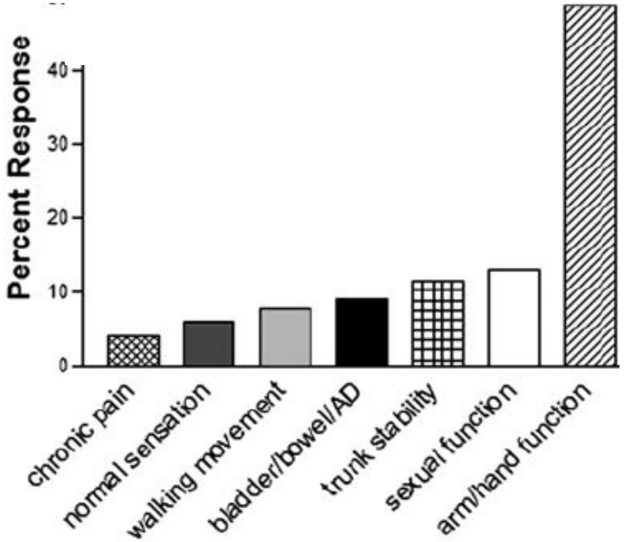
TODAY'S MENU

- robot-assisted neurorehabilitation of the hand function
- neuroscience of rehabilitation

REHABILITATION OF HAND FUNCTION

- the hand is required in everyday activities such as eating, manipulating objects or handwriting

- recovery of hand function is essential to improve the quality of life of stroke survivors



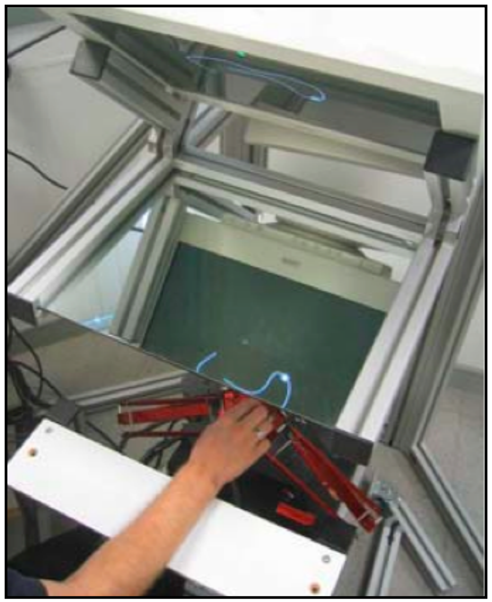
priorities of spinal cord injured population
[Anderson J Neurotrauma 2004]

ARM ROBOTS WITH HAND MODULE

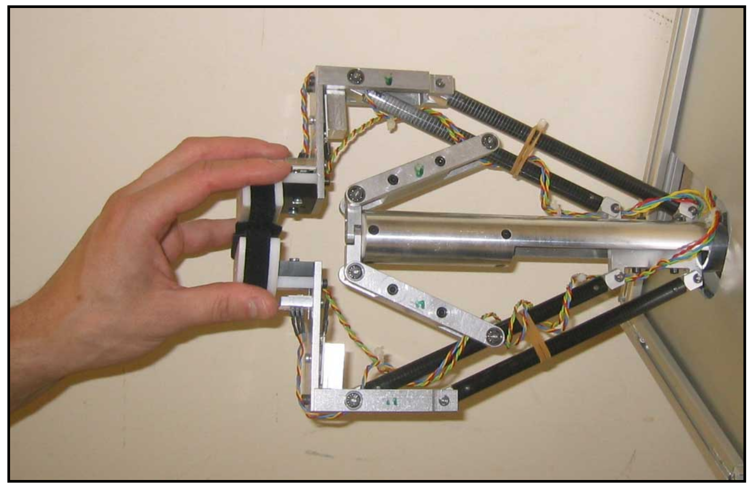
FUNCTIONS THAT CHRONIC STROKE PATIENTS MISS MOST

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

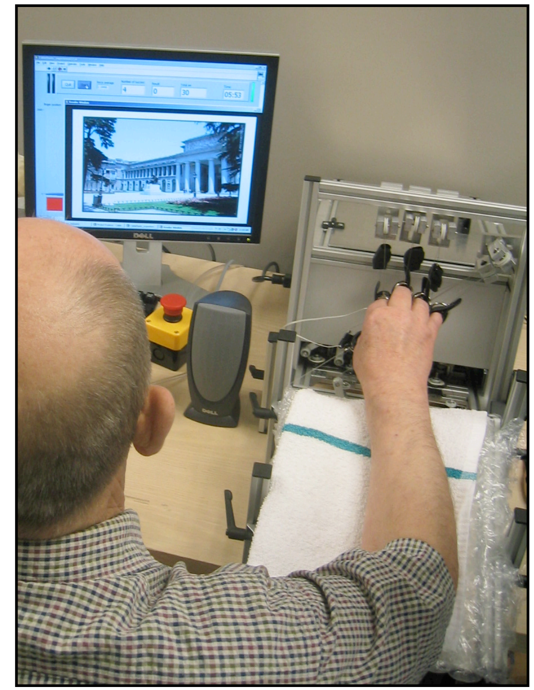
OUR COMPACT DEVICES TO TRAIN HAND FUNCTION



Delta
handwriting and arm reaching



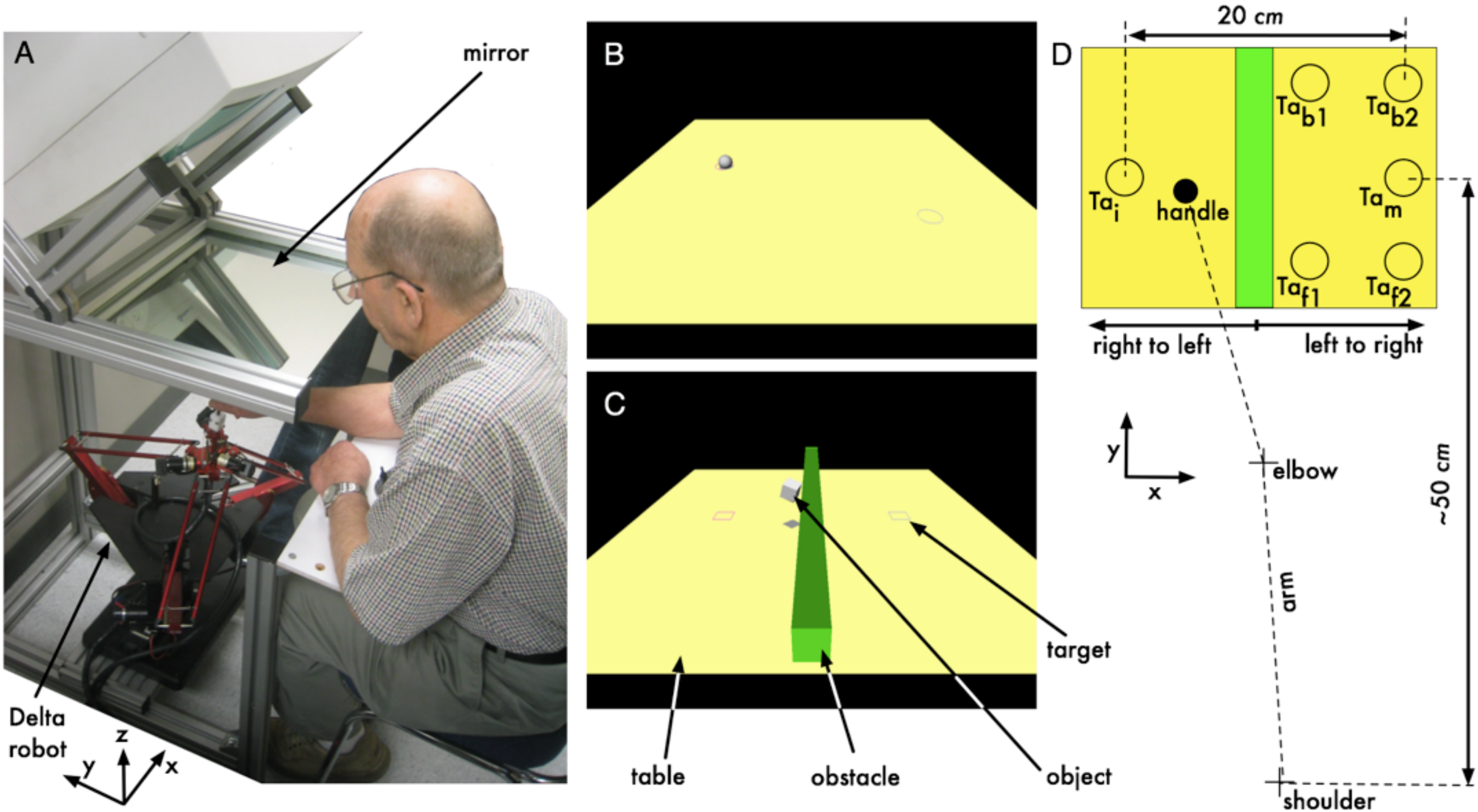
Haptic Knob
hand opening, knob manipulation and grasping



HandCARE
finger coordination and independence, tactile sensation

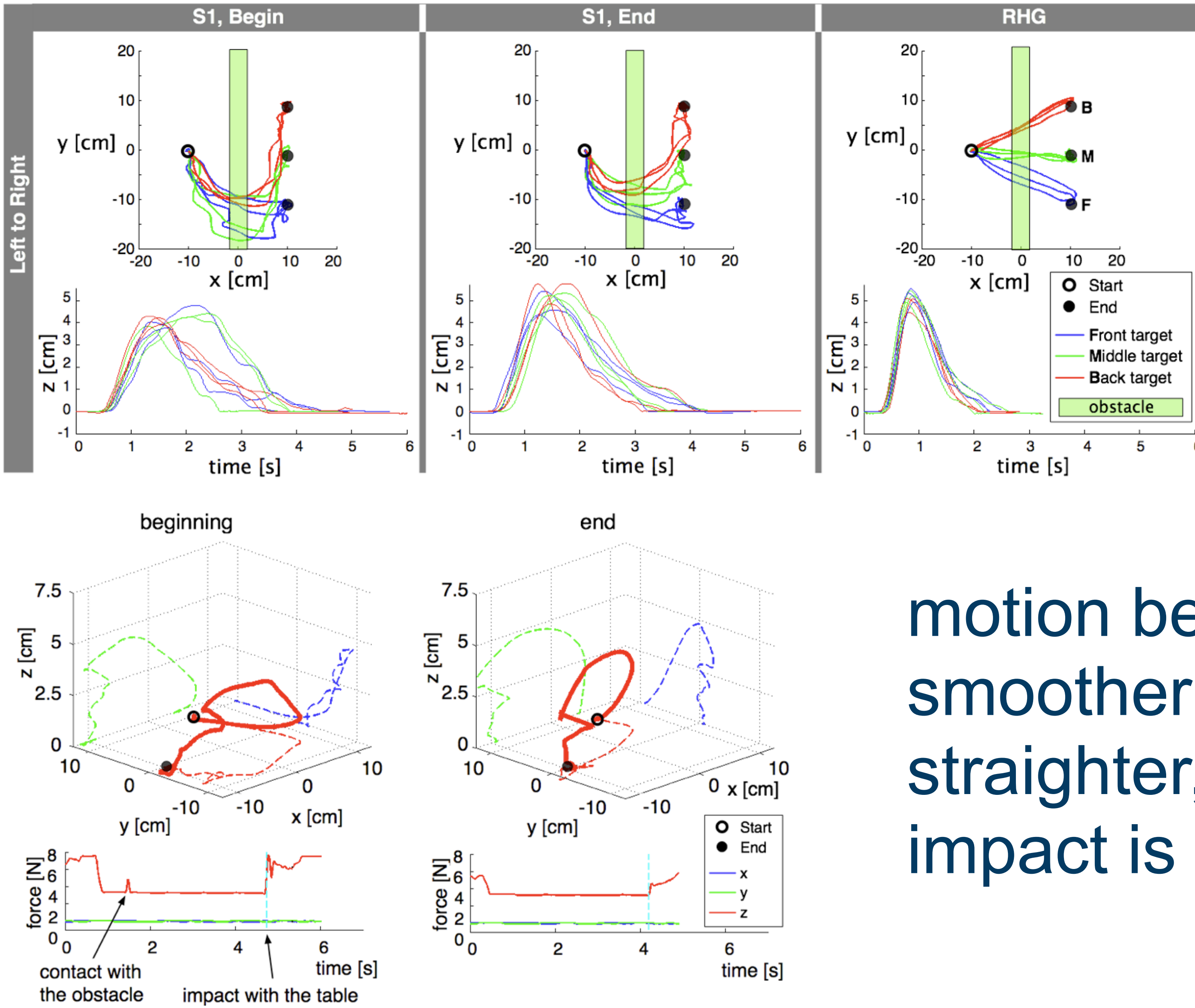
DELTA Workstation

MANIPULATION WITH DELTA



task: to pass a virtual object over a barrier

MANIPULATION WITH DELTA



motion becomes smoother and straighter, and the impact is minimized

[Dovat, Lambercy et al., Proc. Virtual Rehabilitation]

TRAIN FINGER COORDINATION

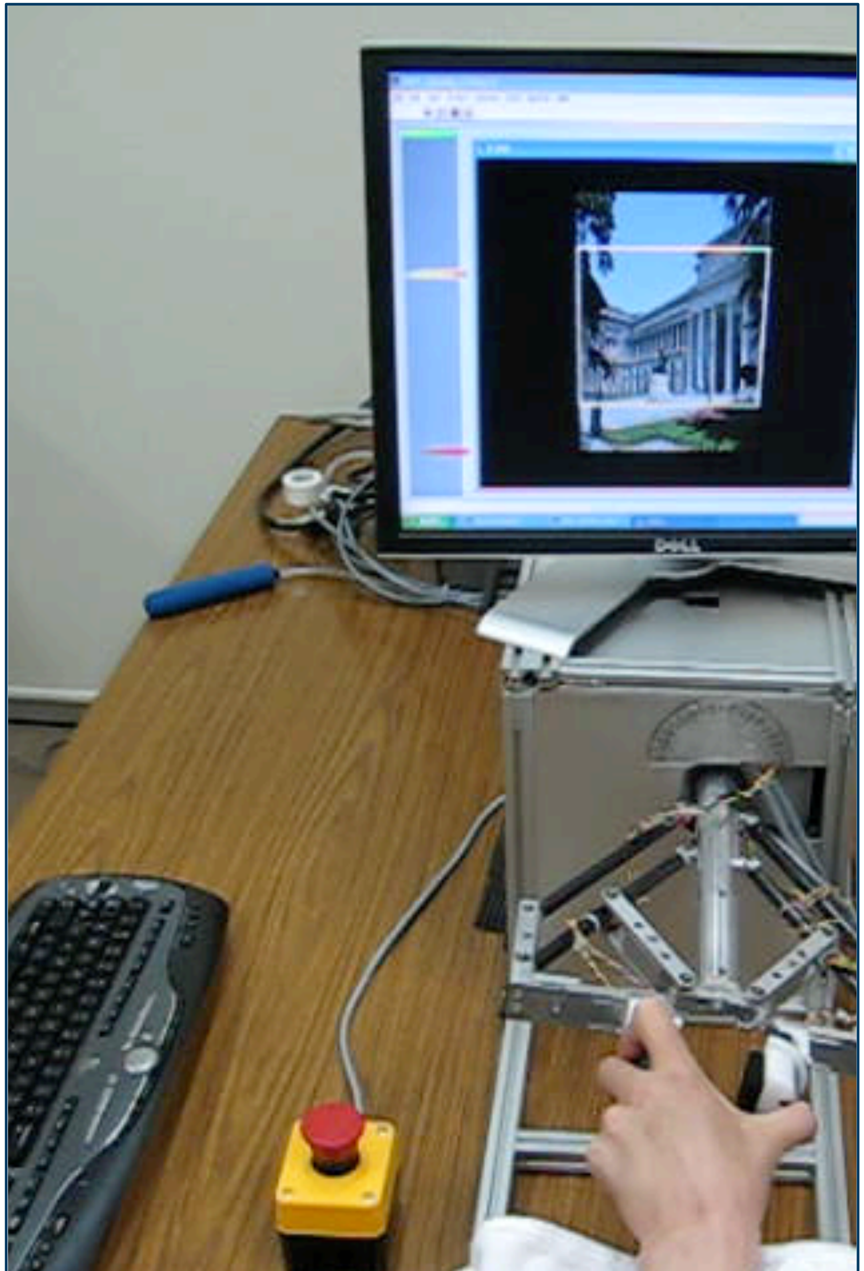
subject
63 years old,
2 years post-stroke,
right hemiplegia

training
8 weeks
16 sessions
20 min/session

instruction: “close the hand against an elastic load while applying the same level of force with the five fingers”

[Dovat, Lambercy et al, i-CREATe 2008]

HAPTIC KNOB: OPENING/CLOSING GAME

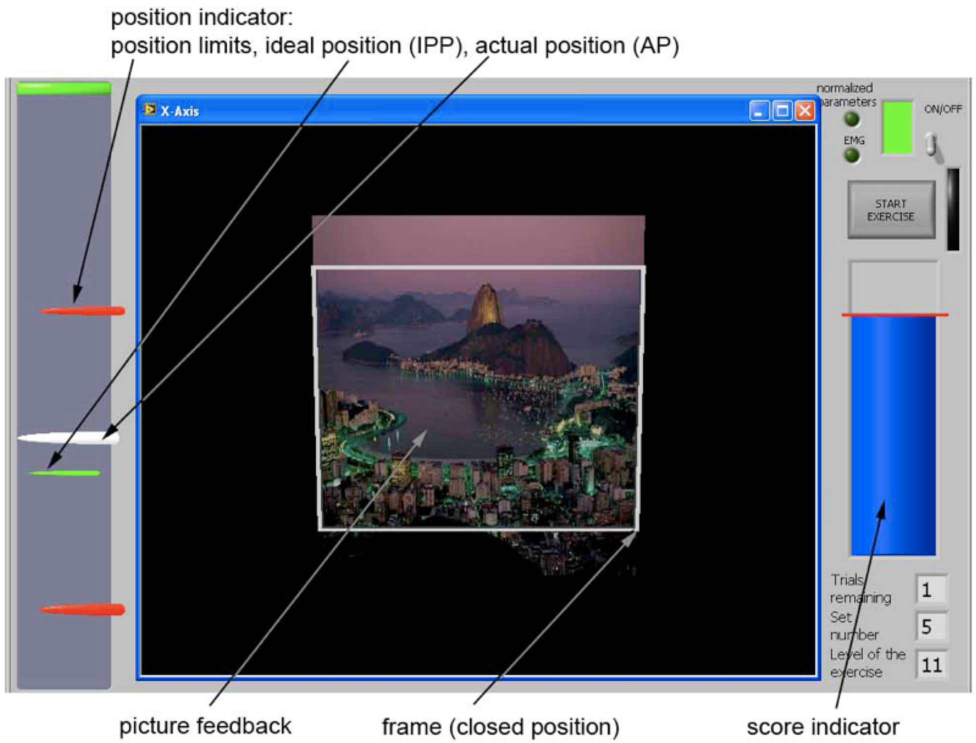


- passive opening to train finger extension
- training slow grasping along a smooth trajectory

Tan Tock Seng HOSPITAL

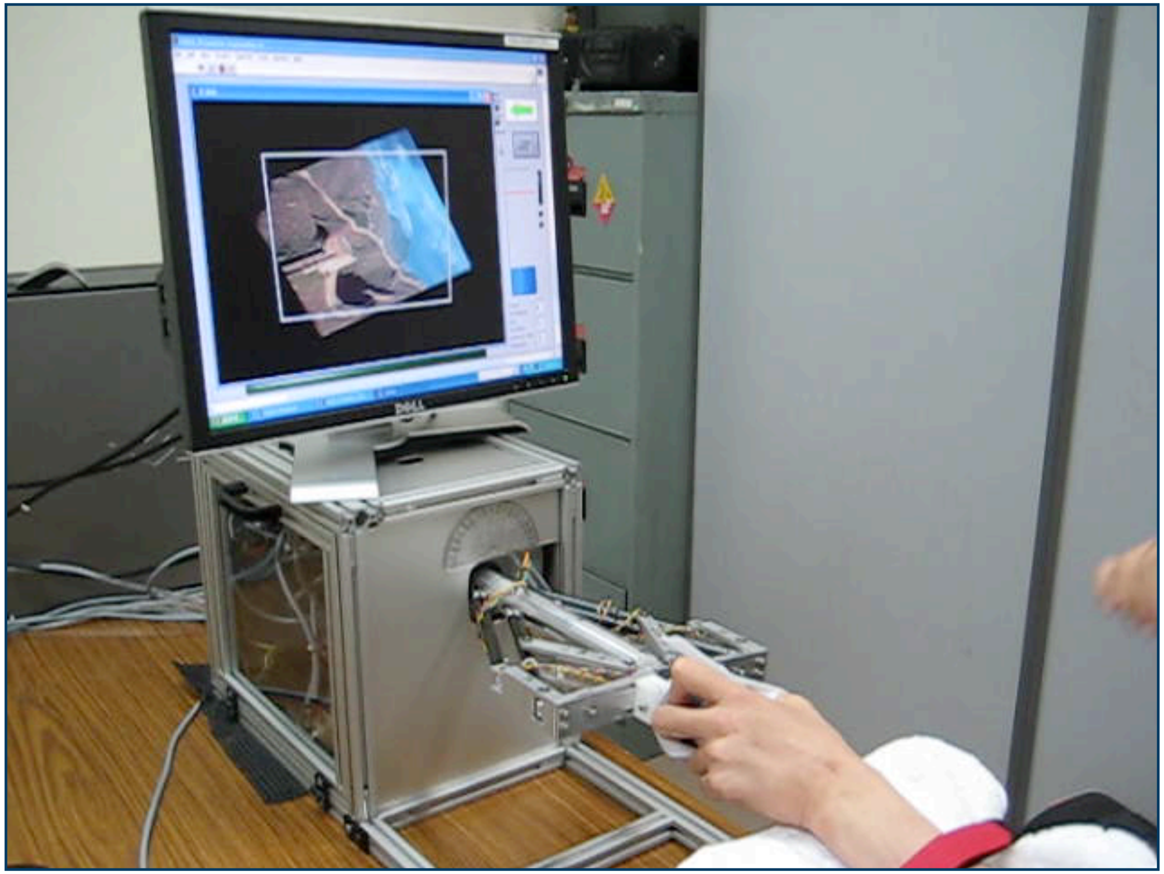
[Lambercy et al. 2011 Journal of NeuroEngineering & Rehabilitation]

OPENING/CLOSING GAME



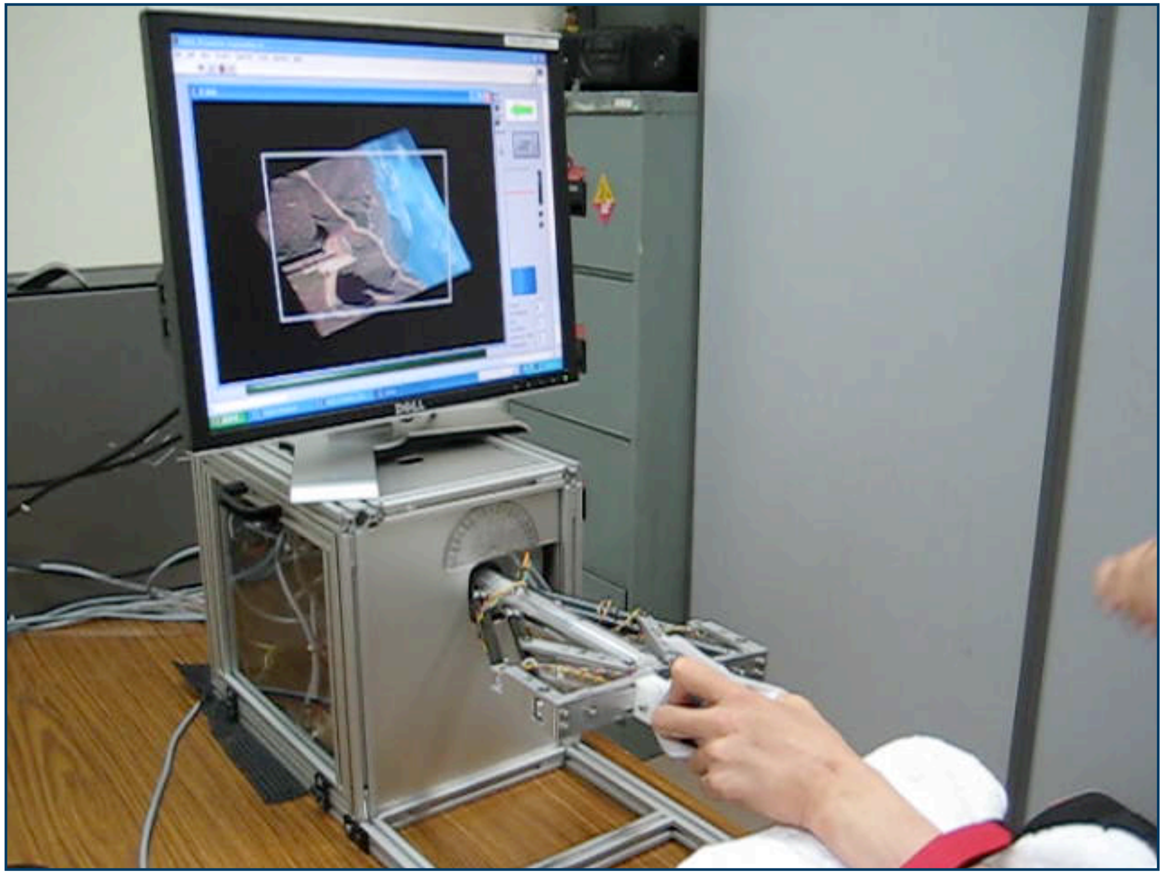
- visual reward when the figure in the frame
- *score = f(precision) + g(smoothness)* to promote progress and motivation
- automatic adaptation of difficulty level with incremental decrease of velocity

PRONATION/SUPINATION GAME



- rotate the figure (of 25^{o}-45^{o}) to a $<2^{o}$ target
- the figure becomes bright when in the frame

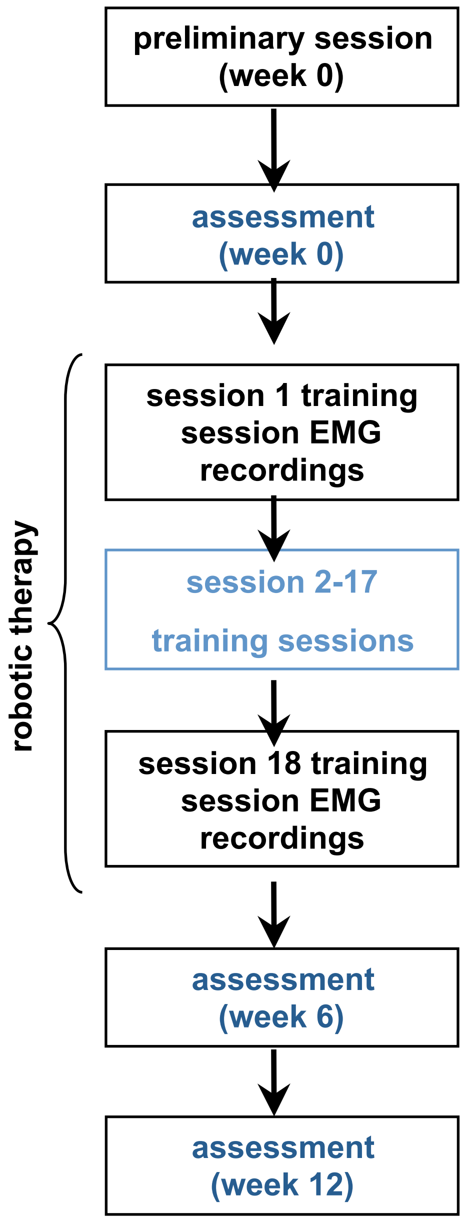
PRONATION/SUPINATION GAME

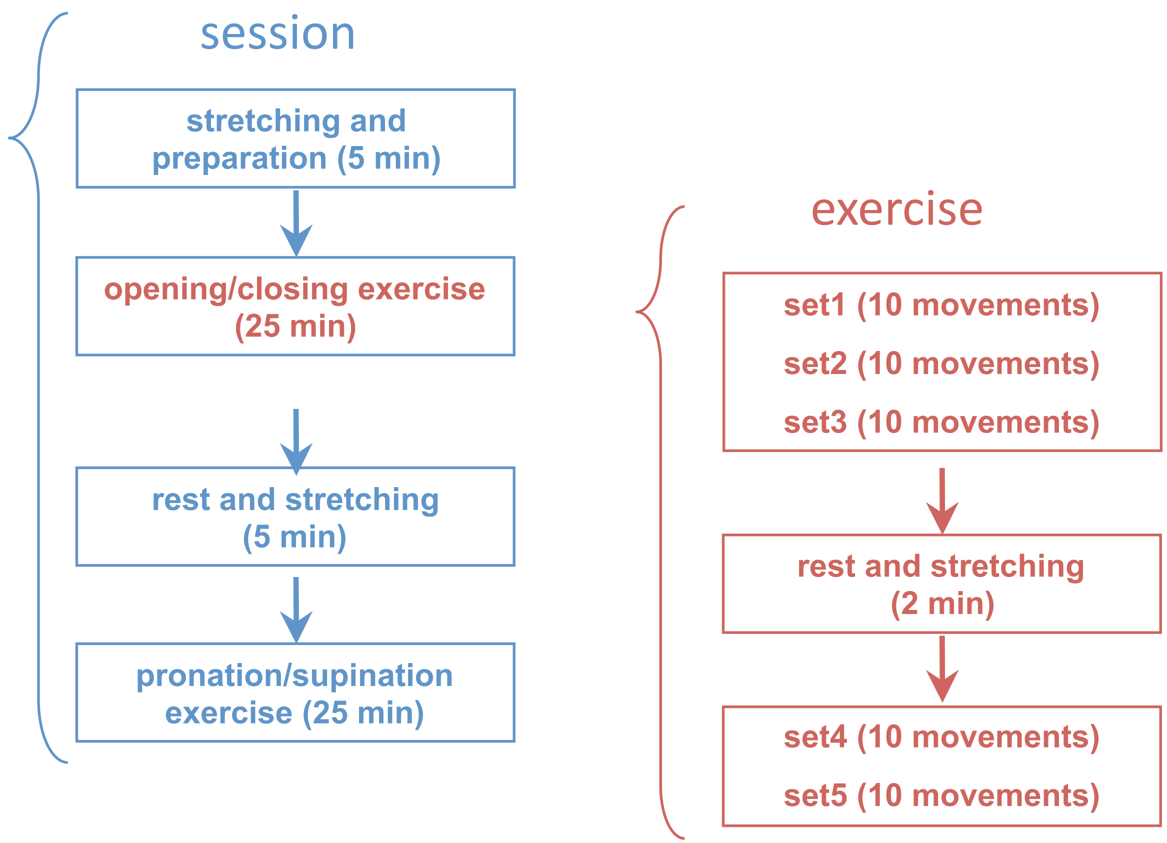


- *score = f(movement time) + g(adjustment time)*
- automatic adaptation of difficulty level with incremental increase of resistive force and required precision

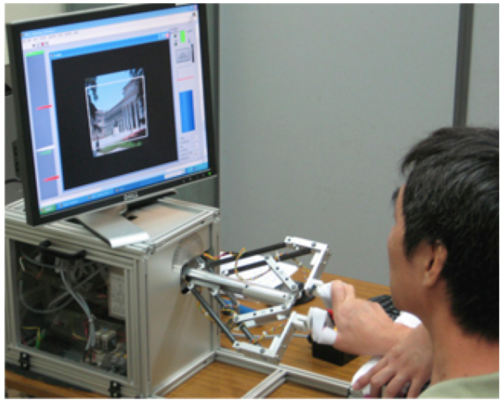
CLINICAL STUDY (1)

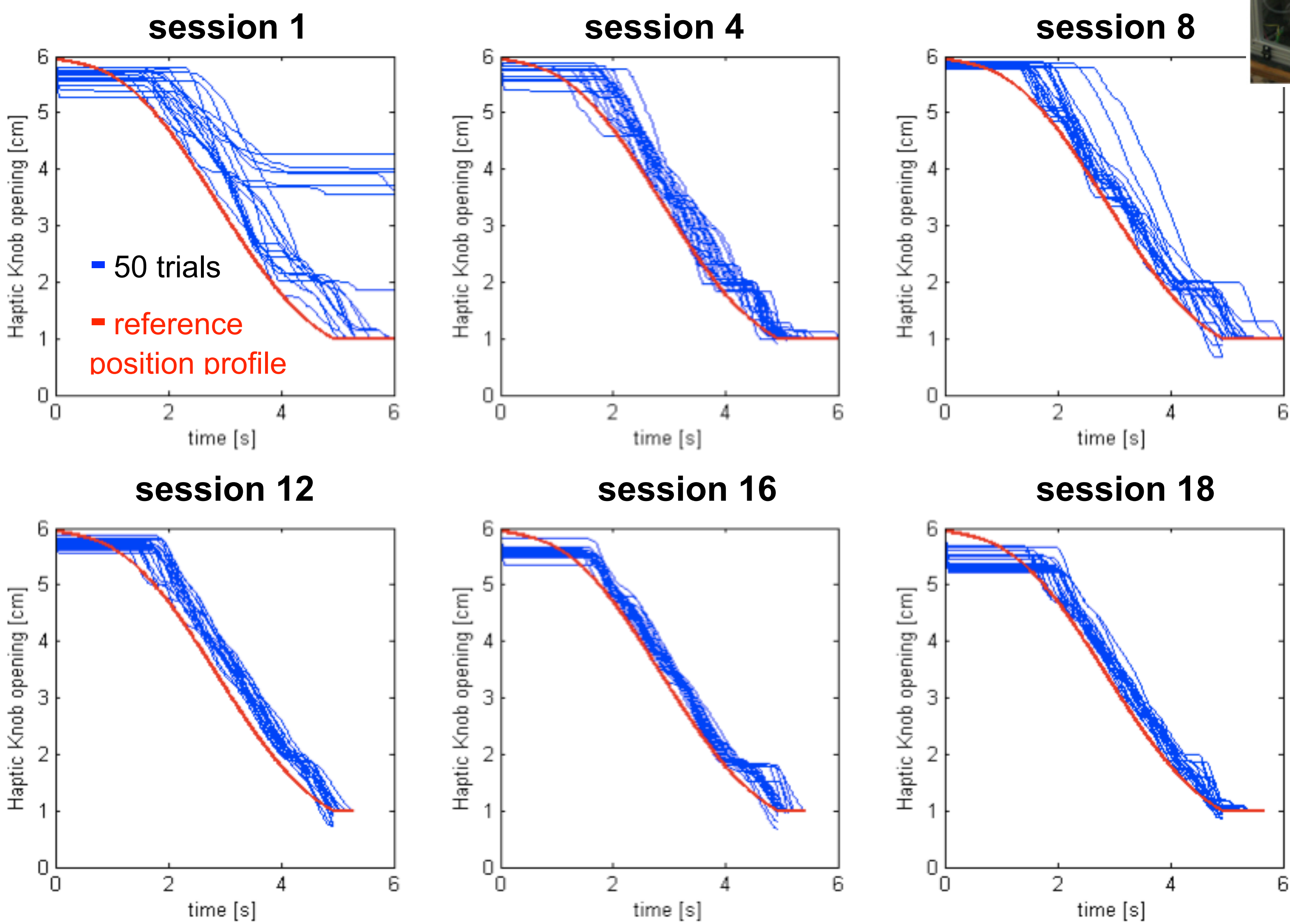
three 1h. sessions/week with the *HapticKnob*, during 6 weeks



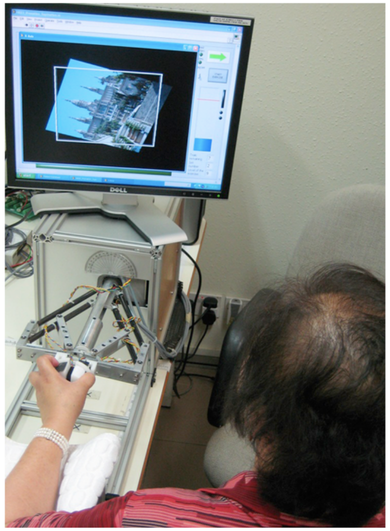


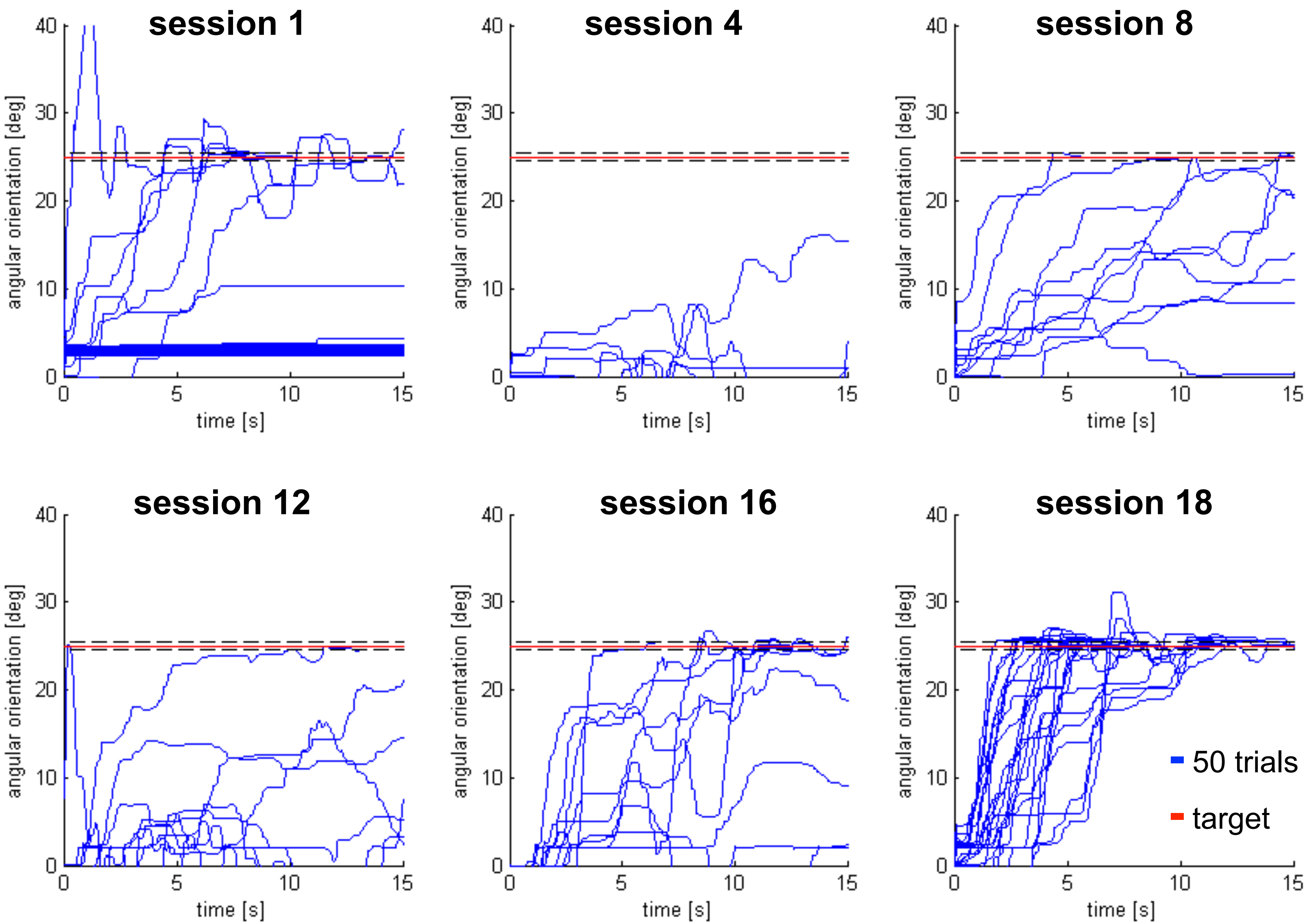
Opening/closing game



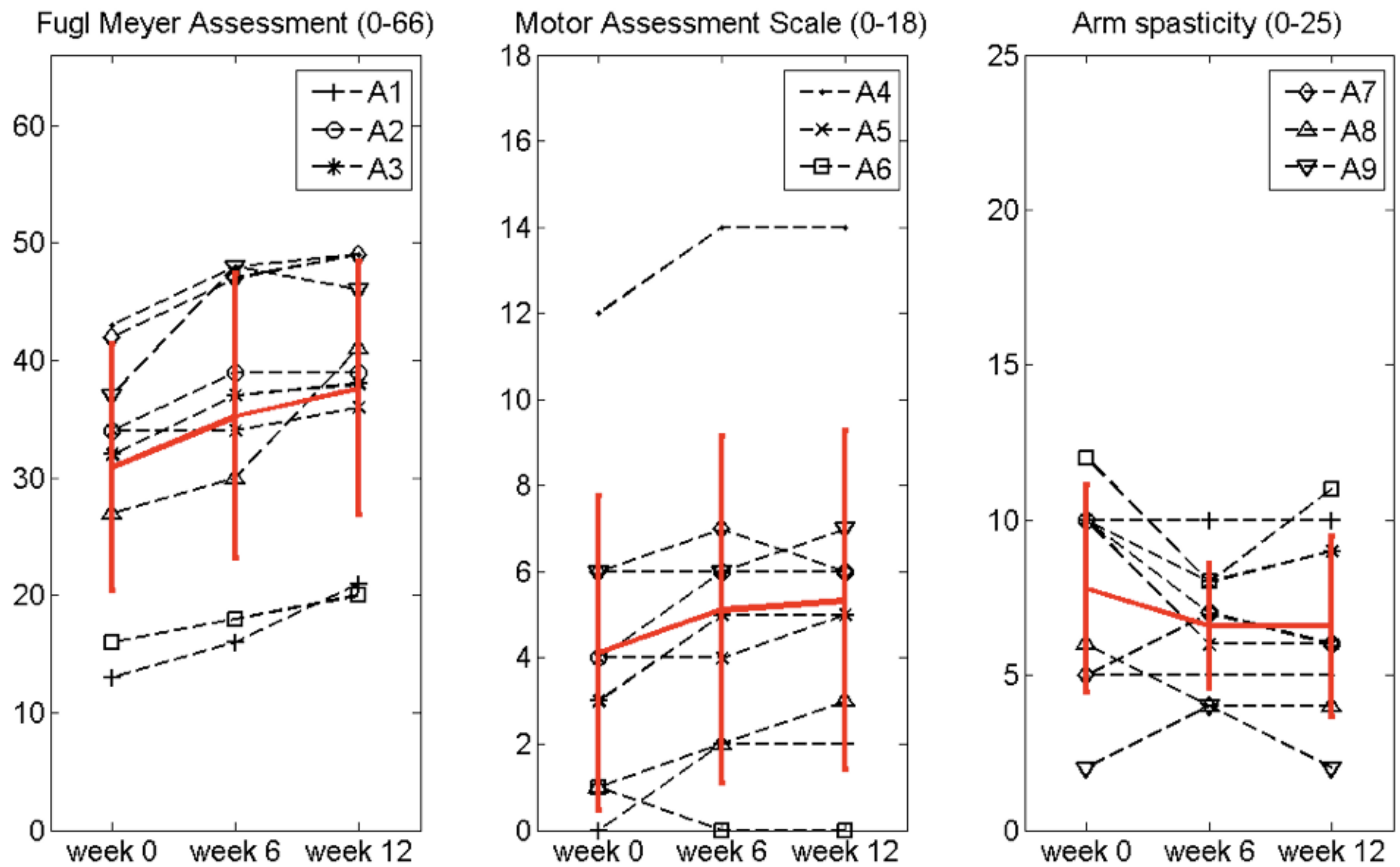


Pronation game





FUNCTIONAL ASSESSMENT



- increase in FM, MAS and decrease of spasticity
- at least maintained 6 weeks after end of therapy
- improvement of hand *and* arm functions

CURRENT REHABILITATION DEVICES

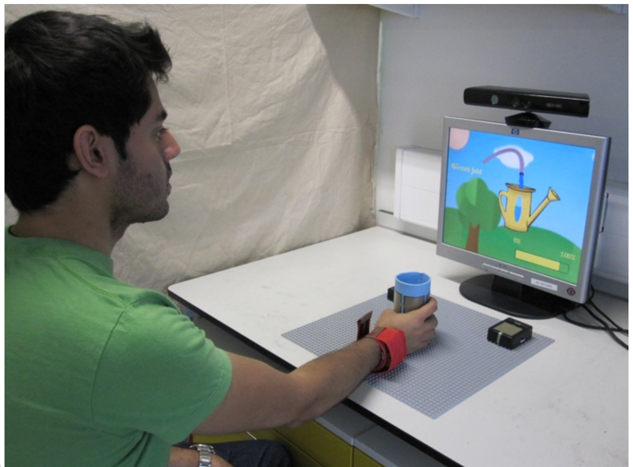
are robots necessary for efficient rehabilitation?

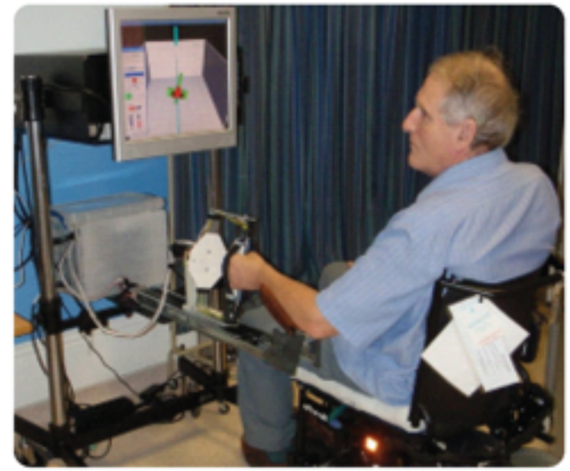
REHABILITATION SYSTEMS

number of potential users / safety

cost / complexity / supervision /technical assisstance

SIMPLE REHABILITATION SYSTEMS





=> find ‘neuroscience shortcuts’ !

Human Robotics
Imperial College

number of potential users / safety

cost / complexity / supervision /technical assisstance

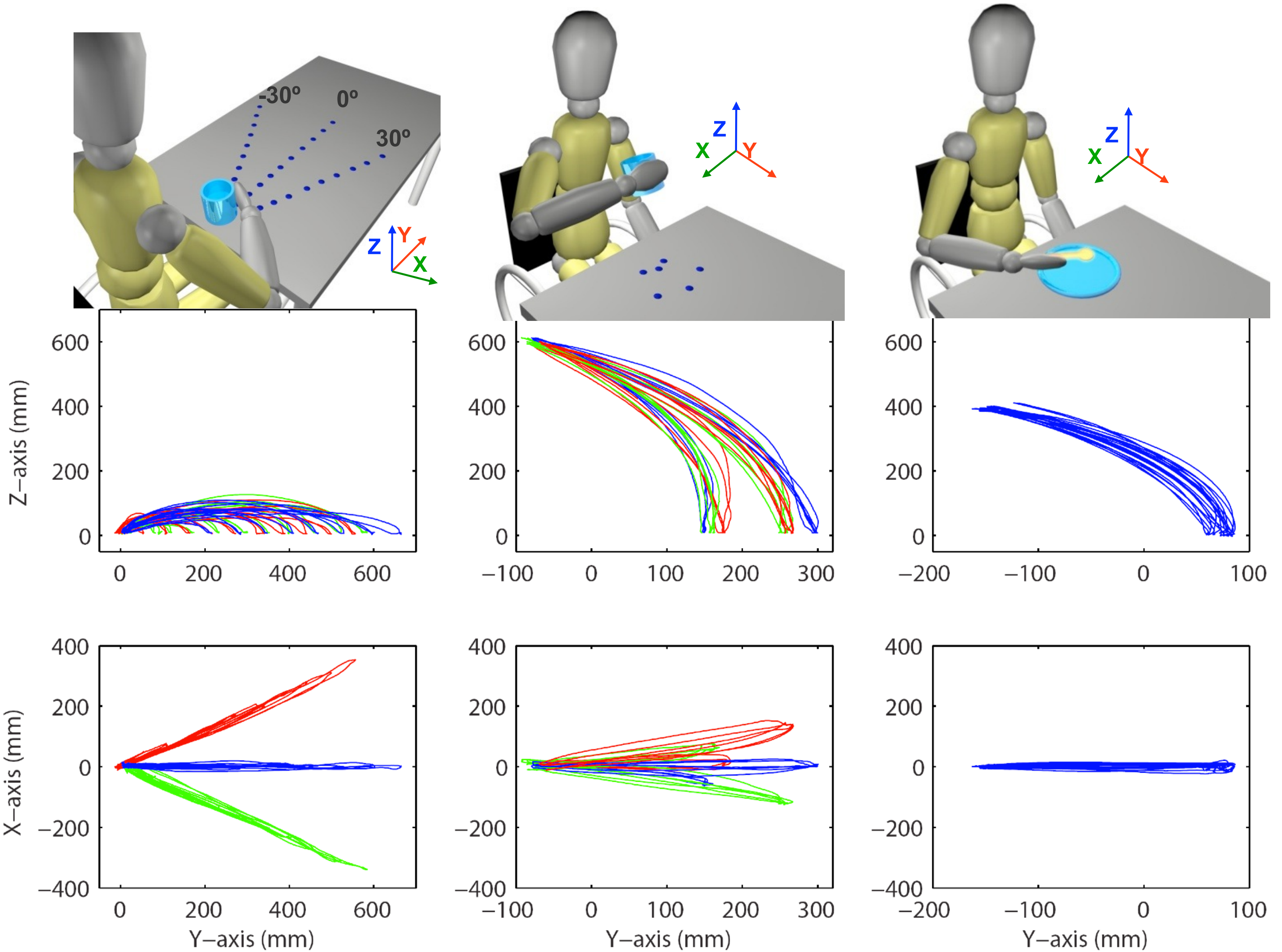
TODAY’S MENU

- robot-assisted neurorehabilitation of the hand function
- neuroscience of rehabilitation

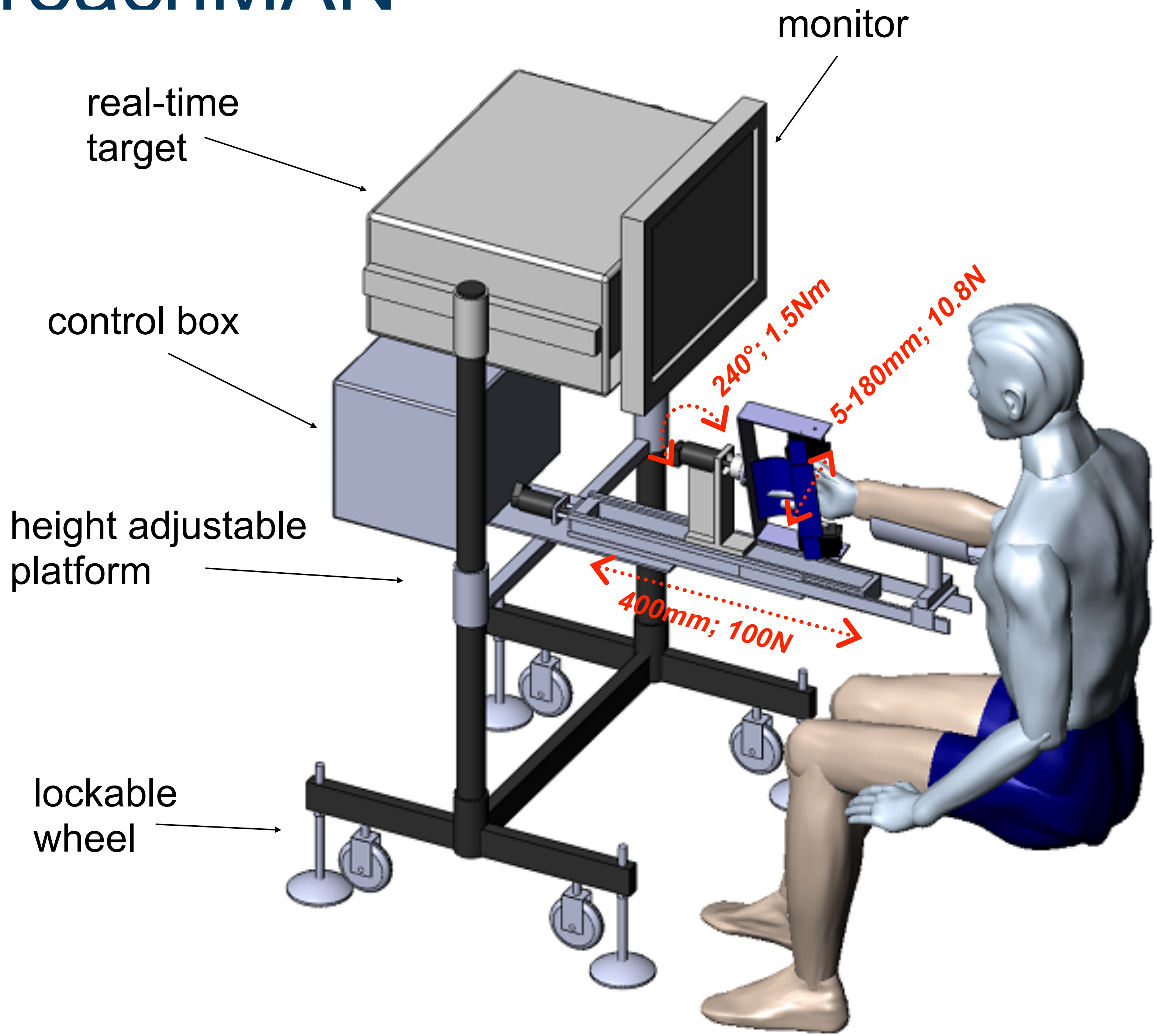
NEUROSCIENCE OF REHABILITATION

- design simplified by considering motor control factors
- experiments with healthy subjects learning a novel task to develop strategies for rehabilitation
- computational neurorehabilitation: models of motor recovery after stroke
- to investigate neural structures and processes involved in rehabilitation

RELY ON NATURAL SYNERGIES TO SIMPLIFY DESIGN

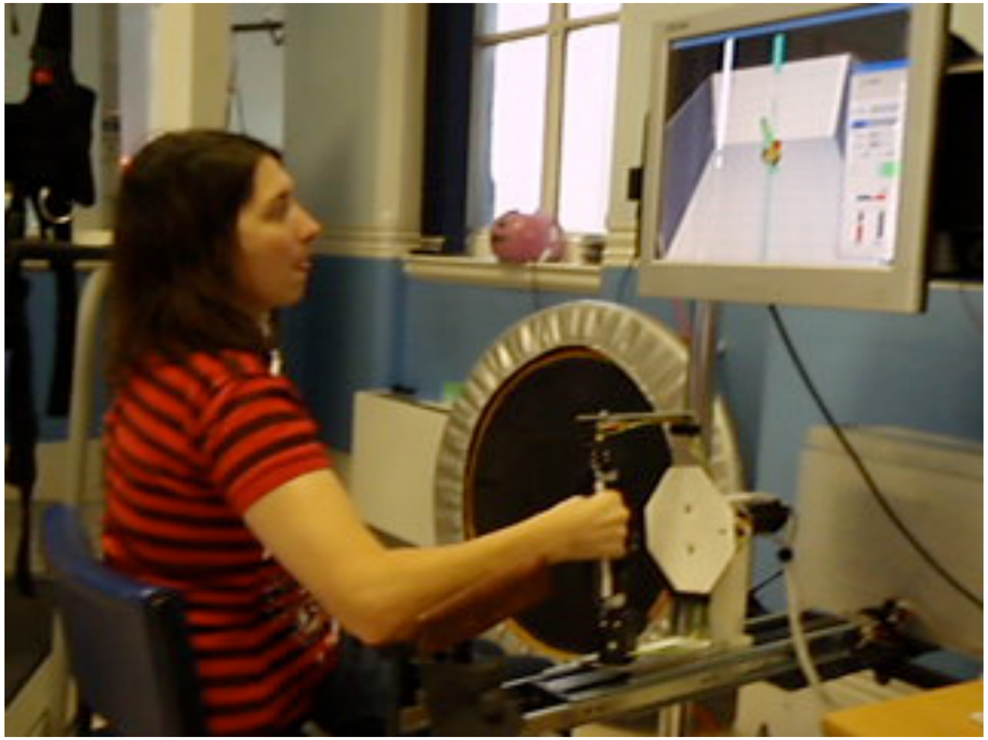


reachMAN

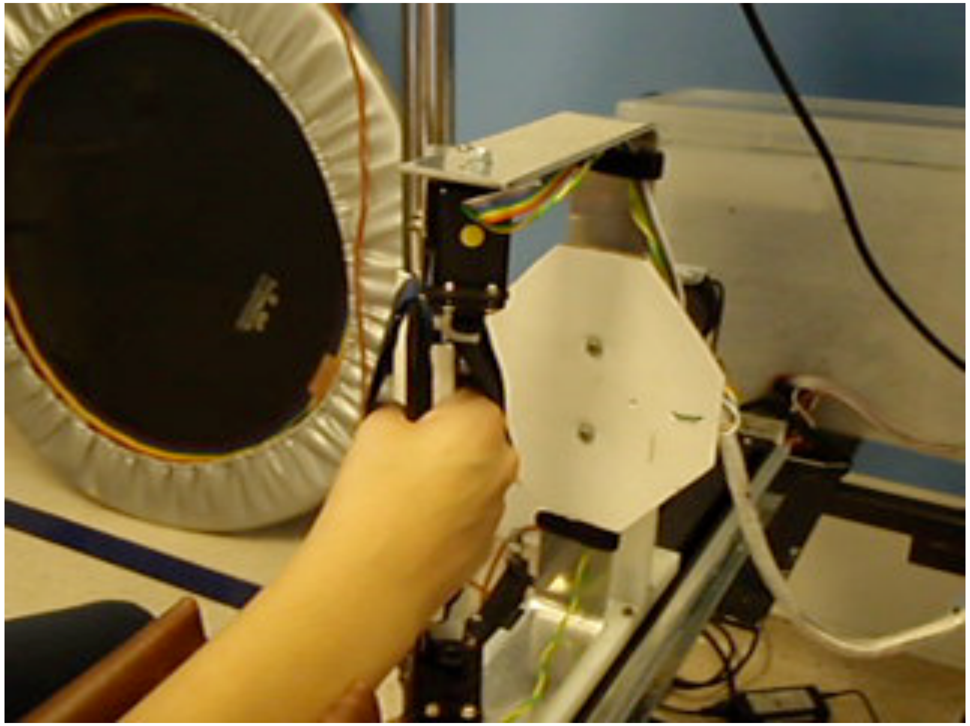

monitor
real-time target
control box
height adjustable platform
lockable wheel
240°; 1.5Nm
5-180mm; 10.8N
400mm; 100N

SUBACUTE TRAINING

pronosupination



reaching

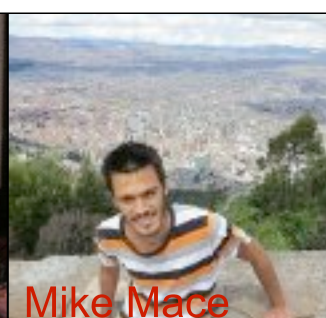


hand opening/closing

ongoing experiment at NHNN, Queen’s square, London

PASSIVE AFFORDABLE SYSTEM

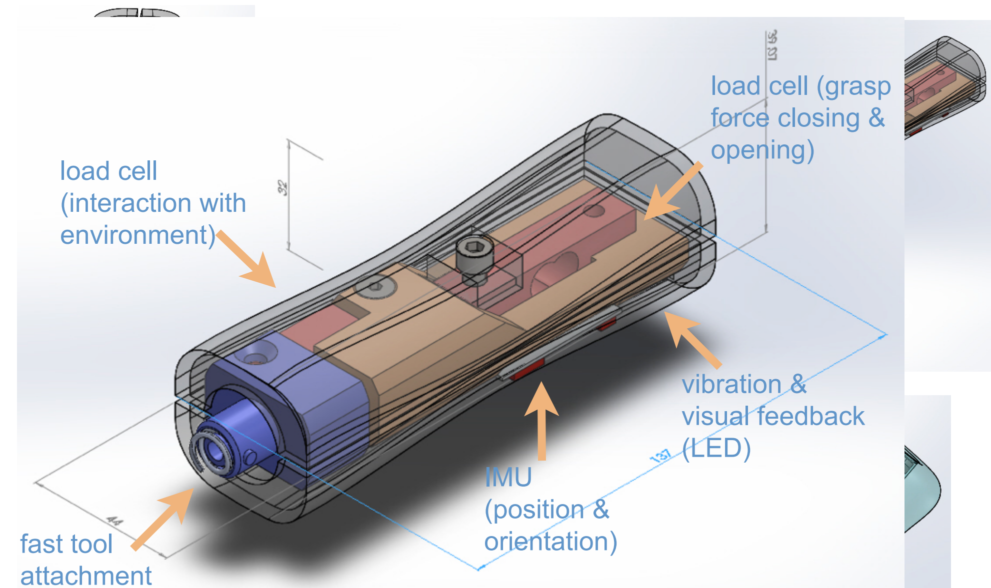
- compliant digital hand grip <100£
- detects even very small forces in flexion & extension without friction
- adjustable size, vibration feedback
- wireless connection to tablet
- attention promoted by distractor
- can be used by 44% of stroke survivors

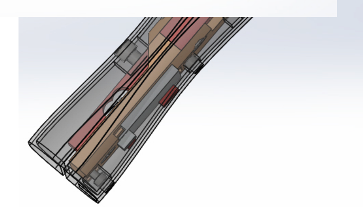


Imperial College Healthcare NHS
NHS Trust

[patent pending]

SITAR system for independent task-oriented assessment and rehabilitation



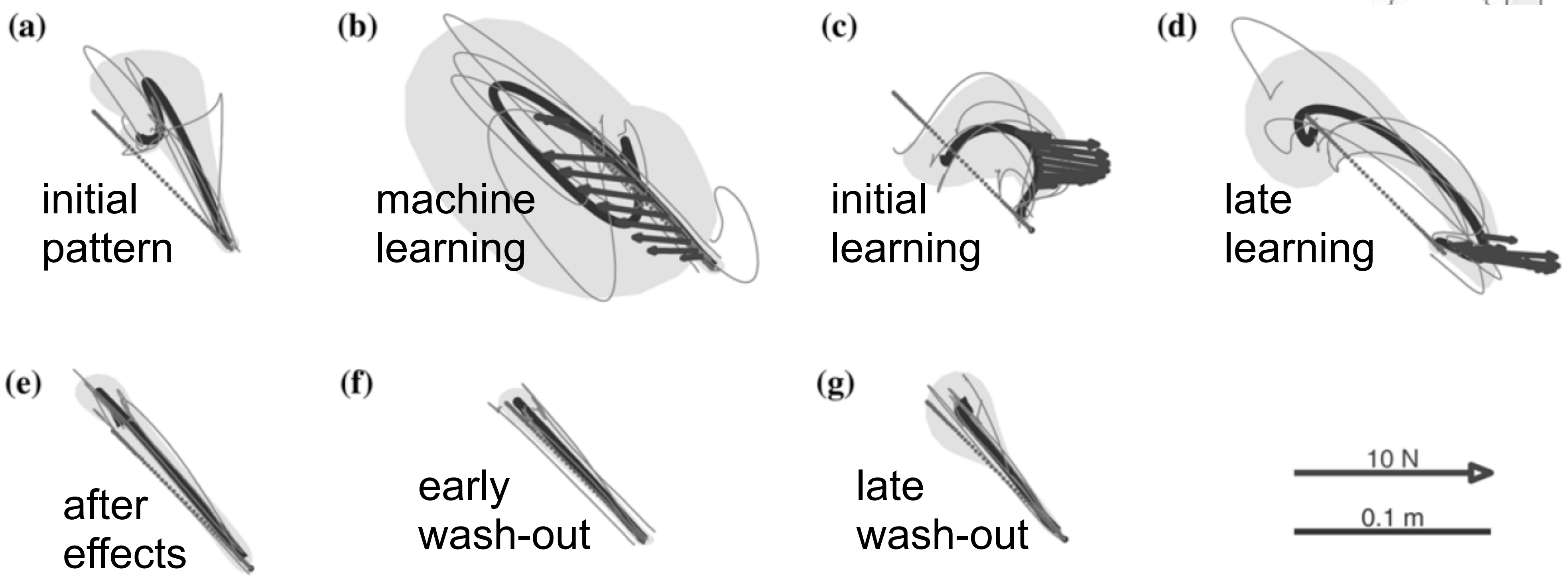


- low-cost force touch screen & intelligent objects
- sensors to infer patient's behaviour
- ongoing assessment study (UCL, CMC Vellore, UPMC)
- ongoing industrialisation

Imperial College London

FORCE FIELDS FOR TEACHING 'CORRECT' MOTION PATTERNS

- force field with 'correct' after effects
- stroke patients can learn a force field
- how permanent is the improvement?



[Patton et al. 2006, J of Rehabilitation R&D]

VIRTUAL LEARNING FOR SIMPLE NEUROREHABILITATION DEVICES

- reaching movements are almost straight
- is it possible to train functional tasks using devices with few DOF?

[Melendez et al. IEEE TNSRE 2011]

VIRTUAL LEARNING FOR SIMPLE NEUROREHABILITATION DEVICES

- reaching movements are almost straight
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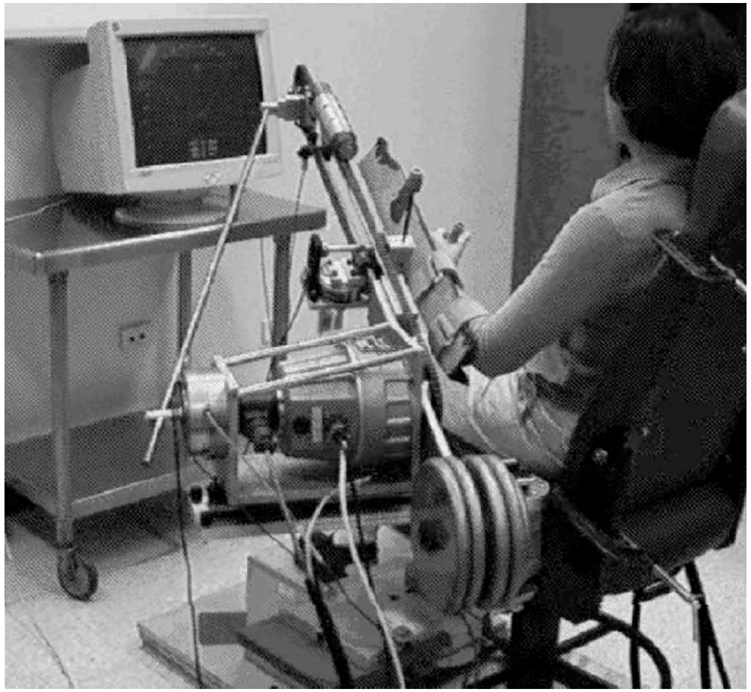
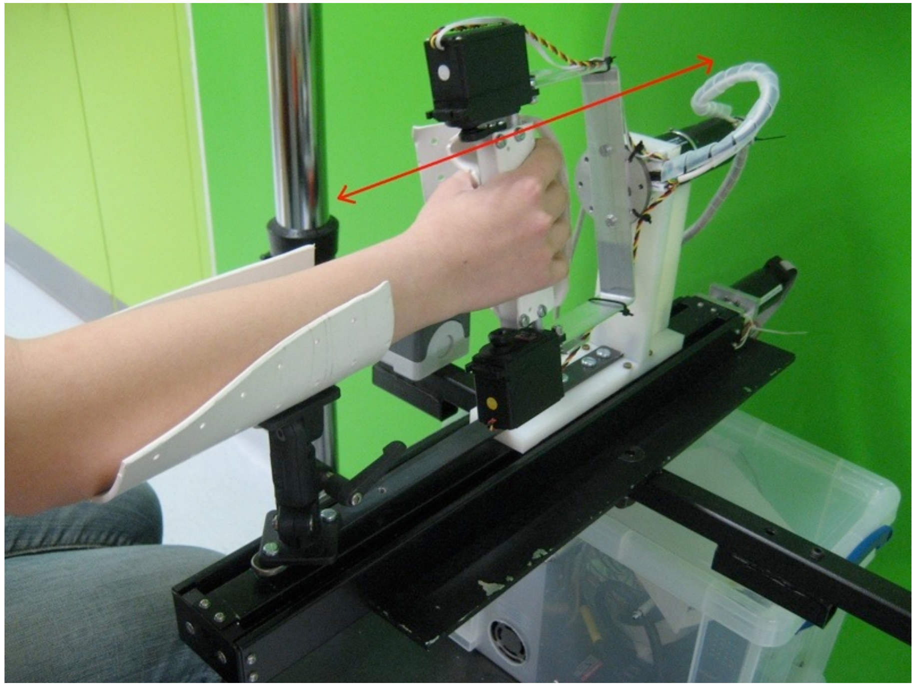


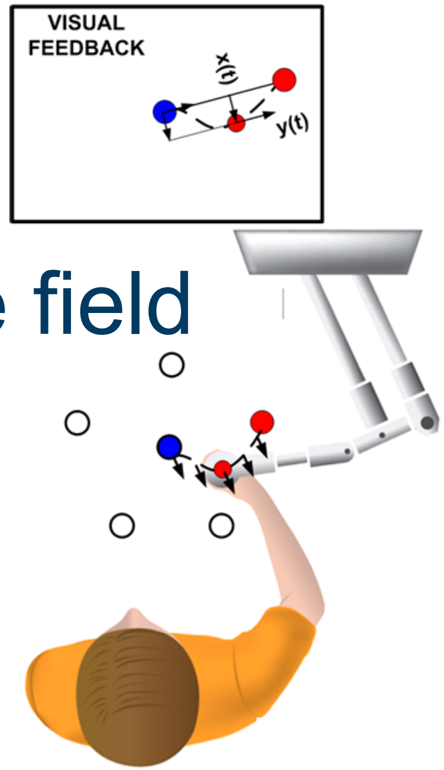
ArmGuide, UC Irvine

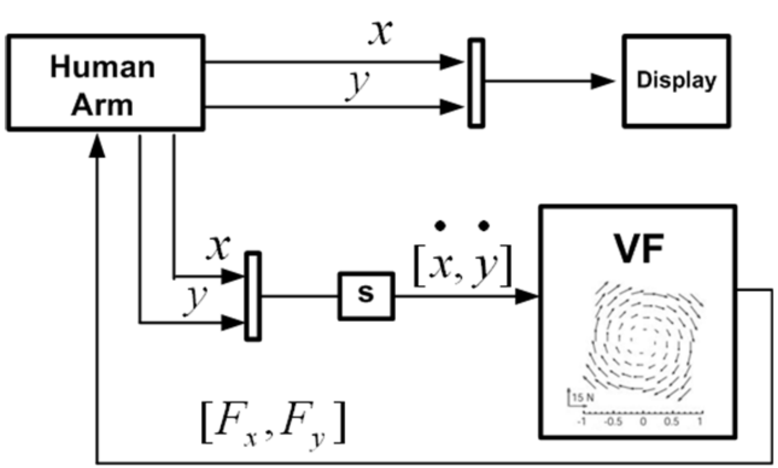


ReachMAN, Imperial College London

TRAINING IN VIRTUAL VF

force field

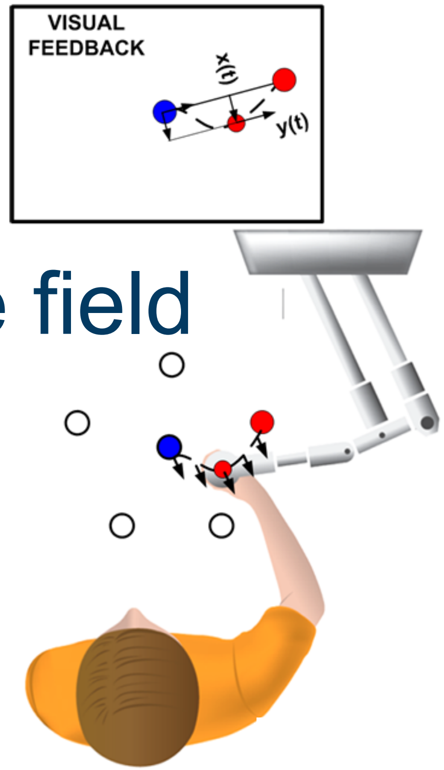


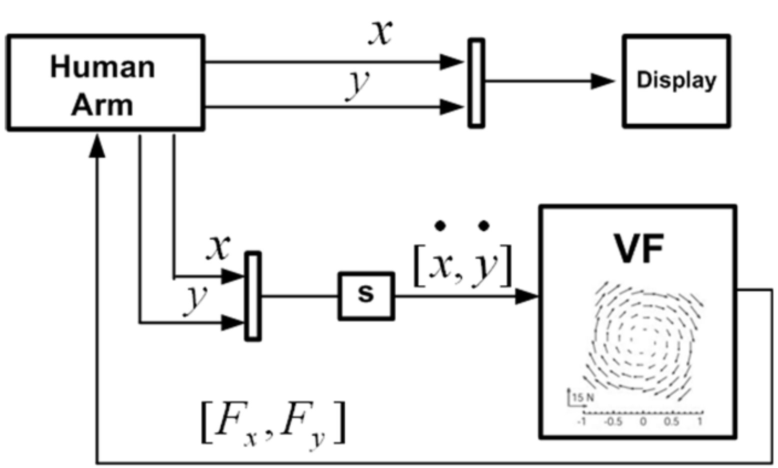


[Melendez et al. IEEE TNSRE 2011]

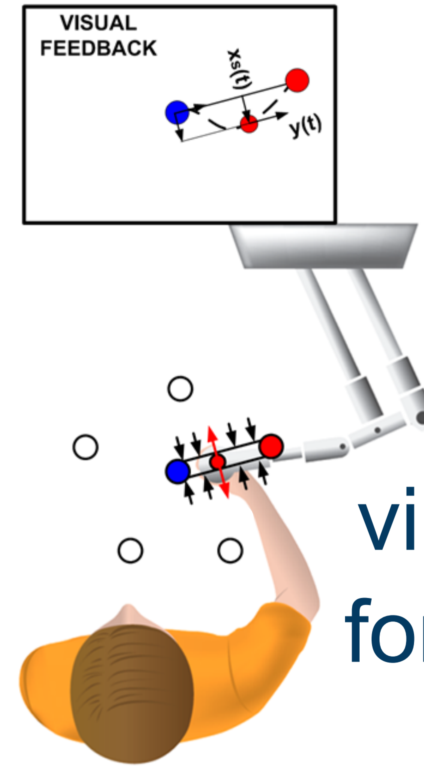
TRAINING IN VIRTUAL VF

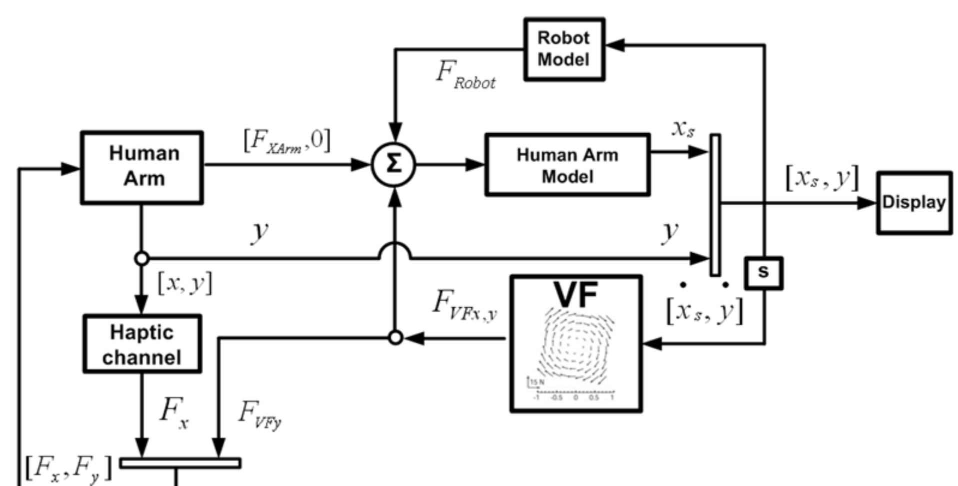
force field





virtual
force field





[Melendez et al. IEEE TNSRE 2011]

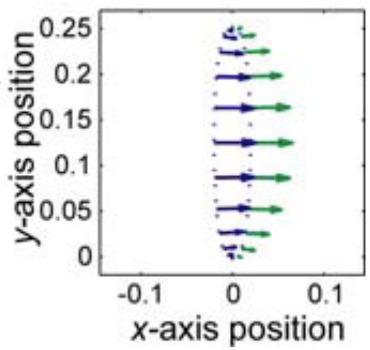
EXPERIMENTAL PROTOCOL

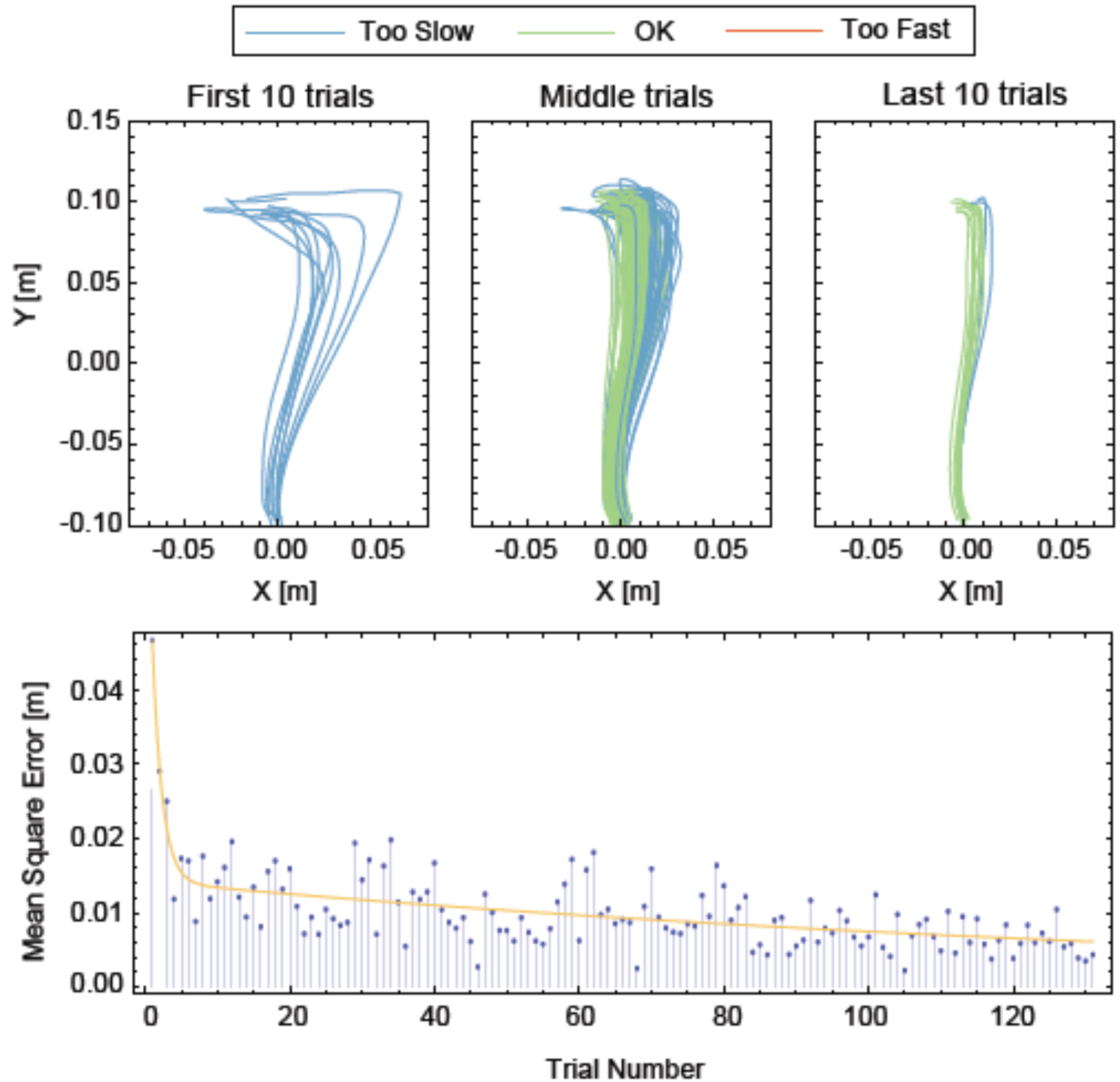
- subjects learn a velocity dependent curl field (VF) in a virtual environment
- proprioceptive error is removed by moving in a haptic channel
- visual feedback of virtual movement is provided based on measured force
- later the subjects perform on the real VF

[Melendez et al. IEEE TNSRE 2011]

LEARNING IN VIRTUAL VF

VF force





virtual trajectories

endpoint error

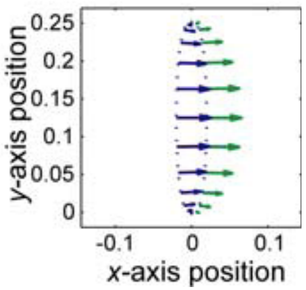
[Melendez et al. IEEE TNSRE 2011]

ANALYSIS OF LEARNING

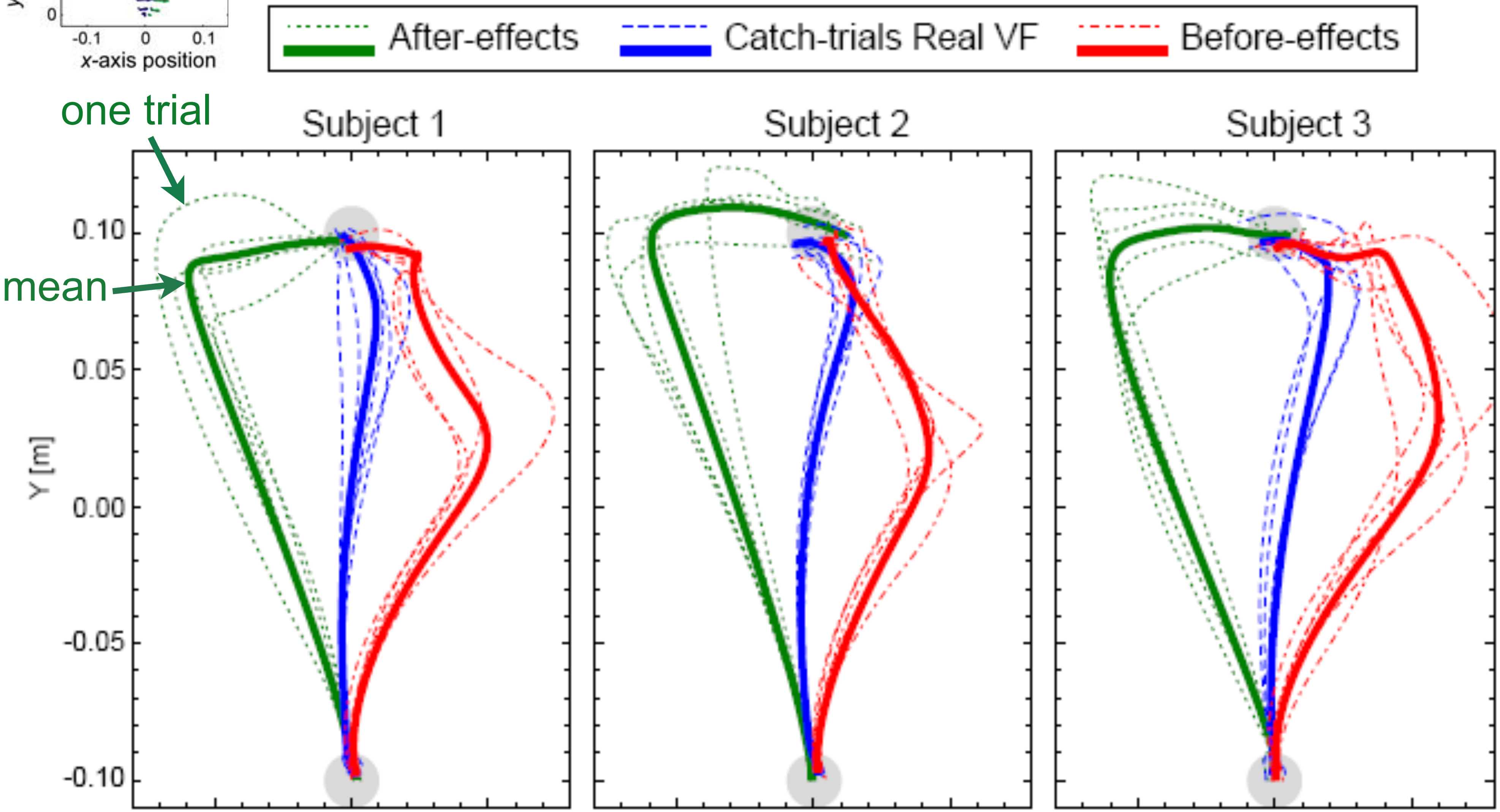
- before effect trials: effect of force field without learning
- after learning trials: effect of force field after learning
- after effect trials: effect of learned dynamics

[Melendez et al. IEEE TNSRE 2011]

VF



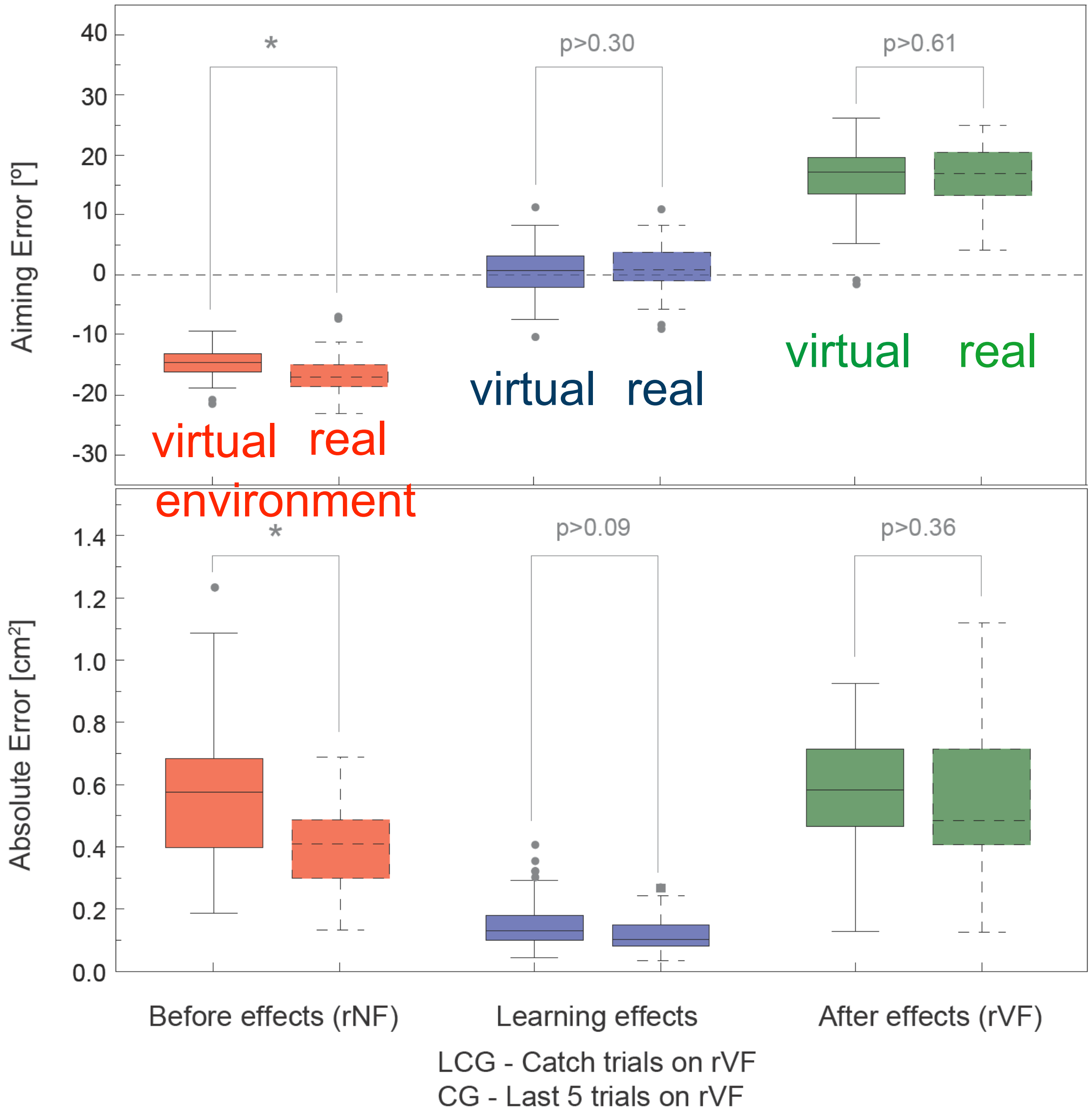
LEARNING IN VIRTUAL VF



efficient learning without proprioceptive feedback

[Melendez et al. IEEE TNSRE 2011]

LEARNING IN VIRTUAL VF



- performance after learning is similar to training in the real environment

- before effects trials are slightly different

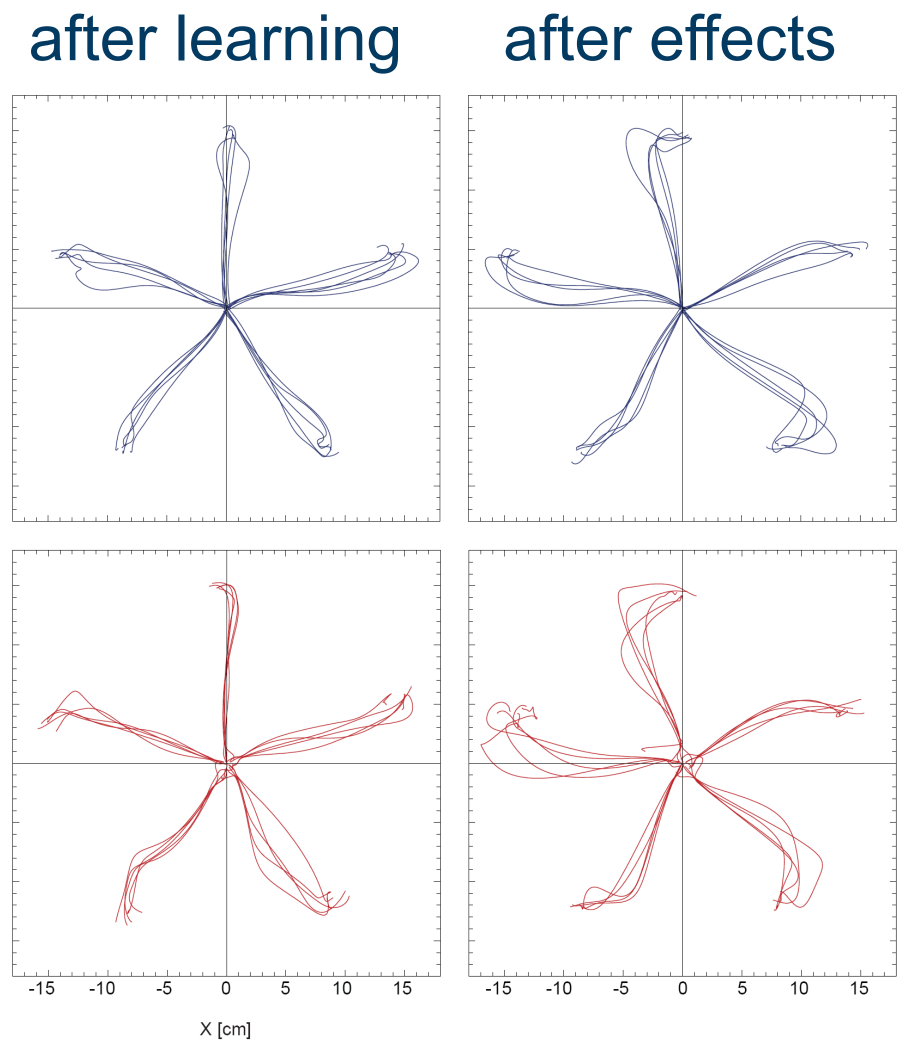
[Melendez et al. IEEE TNSRE 2011]

LEARNING IN MULTIPLE DIRECTIONS

- we have shown motor learning with virtual visual feedback alone along a single movement
- is it possible to learn a force field without proprioceptive feedback?

[Melendez et al. IEEE TNSRE 2011]

LEARNING IN MULTIPLE DIRECTIONS



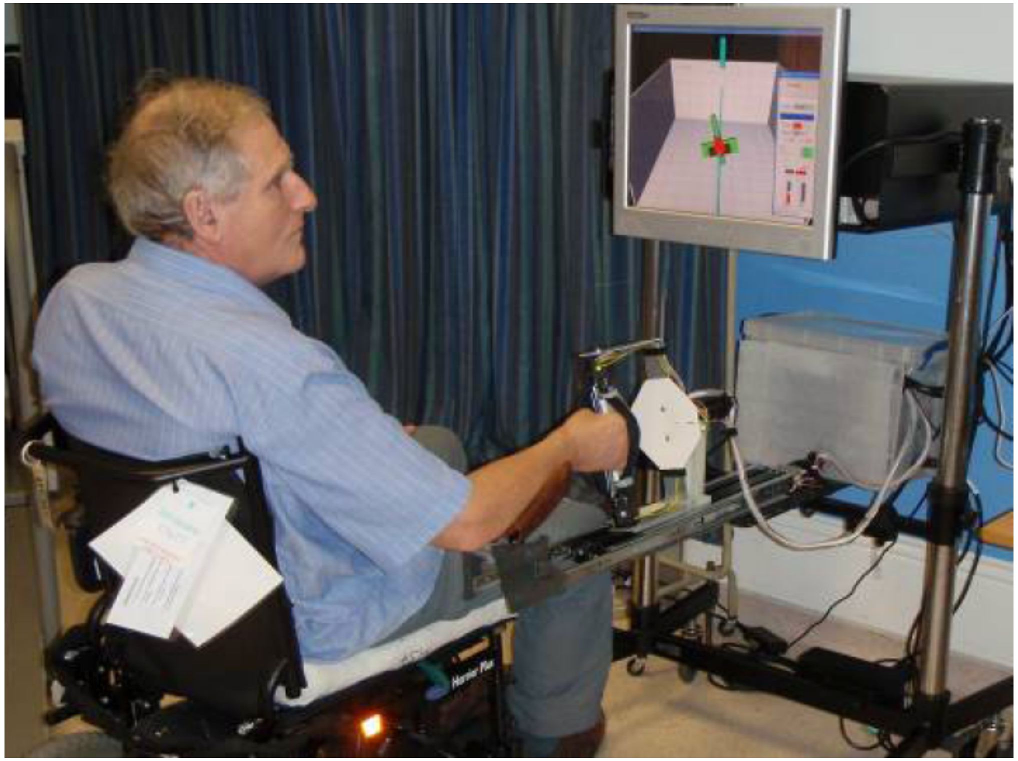
conventional learning

training with virtual force field

- efficient learning in the virtual force field
- end of trajectory slightly different, maybe due to the dynamic model used

[Melendez et al. IEEE TNSRE 2011]

TAKE HOME



- it is possible to learn force fields without proprioceptive error
- using visual feedback of the error corresponding to the exerted force (conflicting with the hand traj)
- this suggests simple training devices

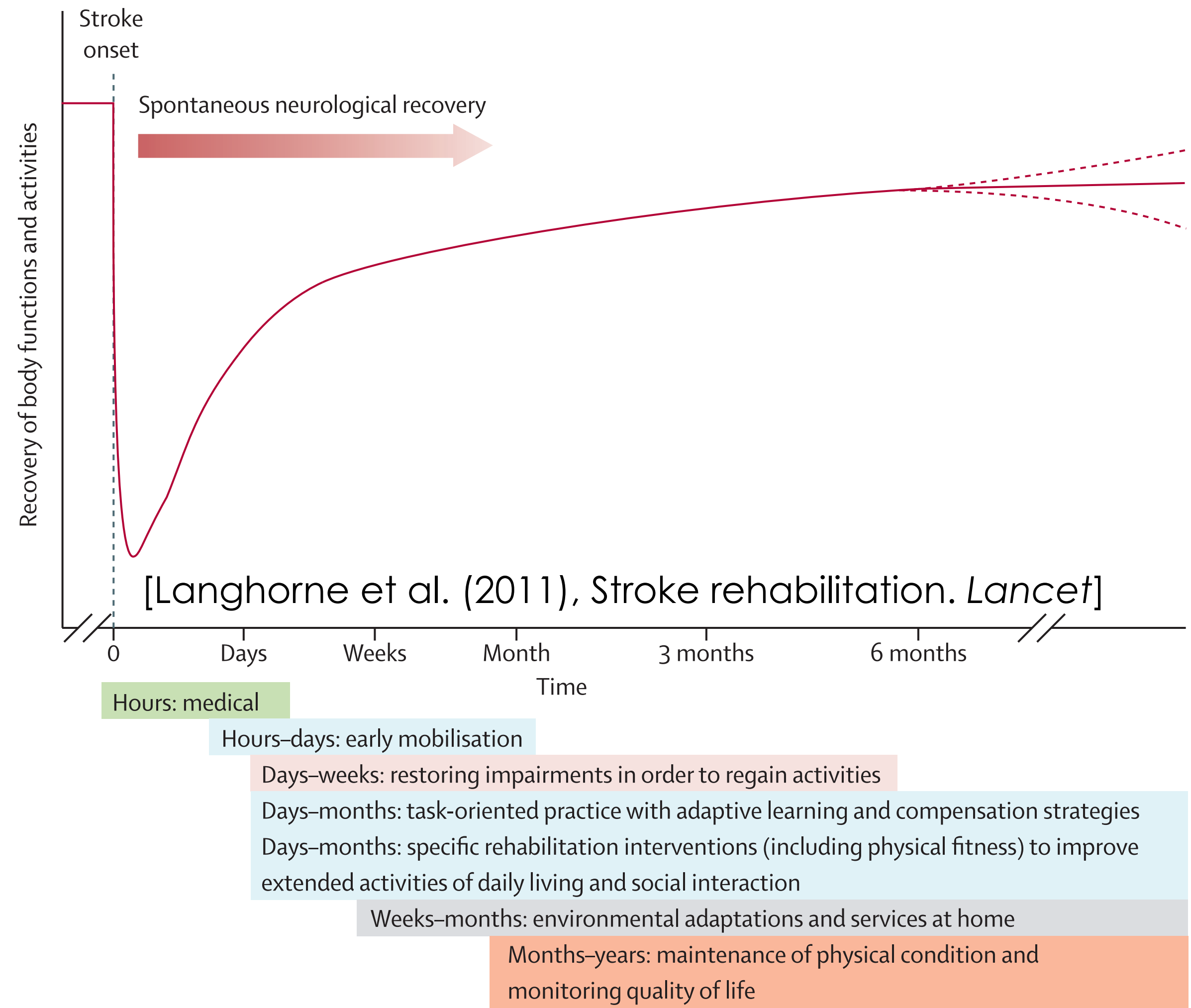
MODELS OF MOTOR RECOVERY AFTER STROKE

Why modelling recovery?

- better understanding on the nature of the recovery process
- basis for planning and delivery of therapy
- towards control of the recovery process through the administration of appropriate clinical interventions

Pattern of recovery after stroke

- qualitative models of the recovery pattern
- no predictive ability and no subject specific recovery description
- little clinical utility



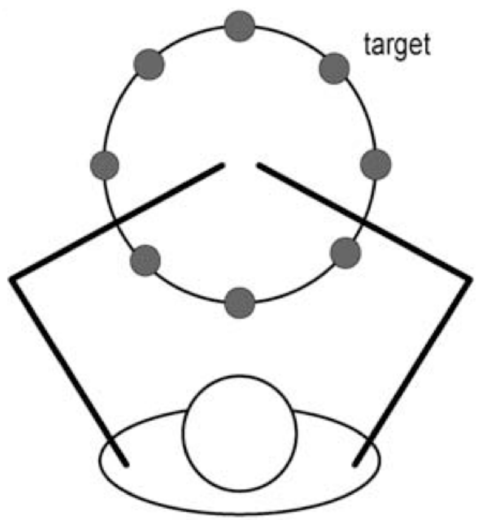
[Langhorne et al. (2011), Stroke rehabilitation. *Lancet*]

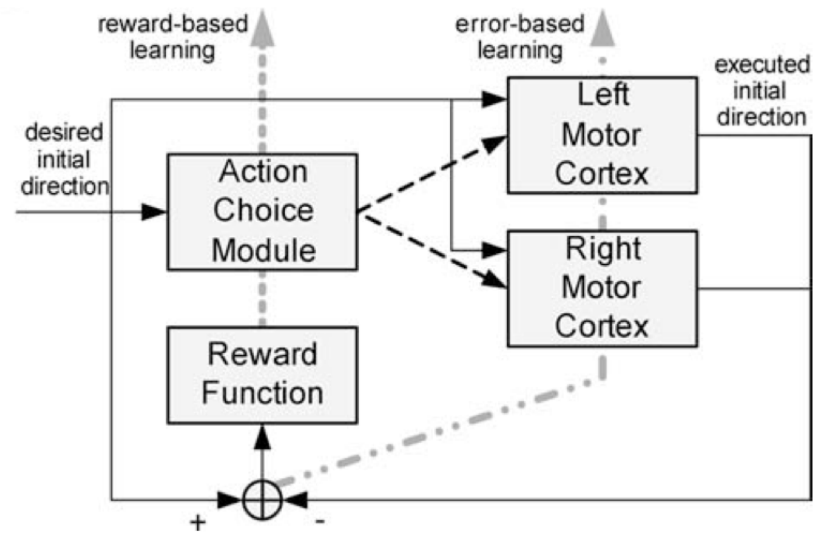
Current models of motor recovery after stroke

- *Schweighofer et al.*
  prediction of preferred arm during recovery

- *Casadio and Sanguineti, Colombo et al.*
  linear state space model of recovery

Prediction of preferred arm during recovery

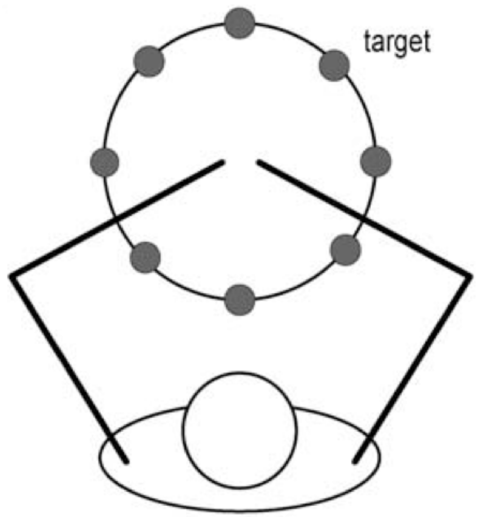


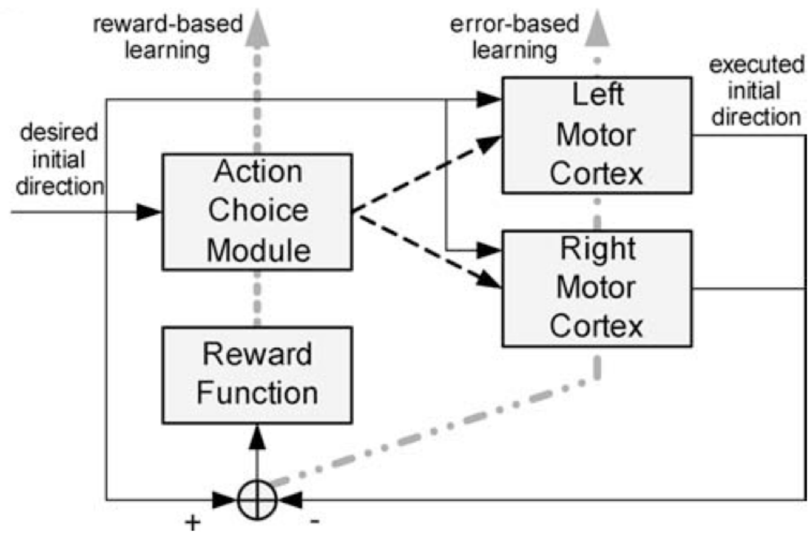


- to simulate the effect of learned non-use and its reversal with constrained induced therapy
- model of arm choice (left or right) for reaching

[Han et al. (2008), Stroke rehabilitation reaches a threshold. *PLoS Computational Biology*]

Prediction of preferred arm during recovery



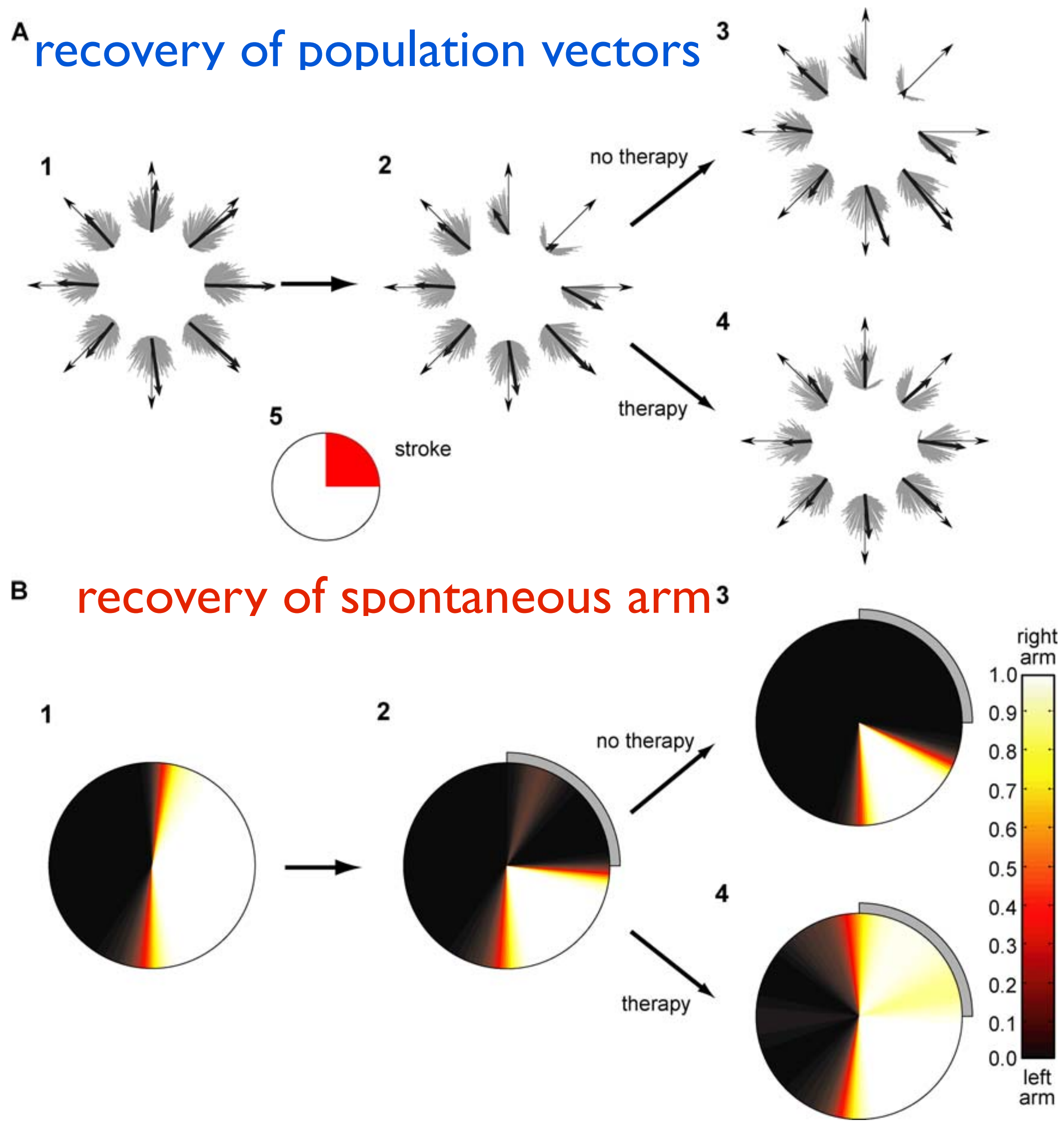


- choice between right and left arm
- weighted average of neurons preferred direction
- arm selection for short distance and max performance
- Hebbian and error based learning of weighting

[Han et al. (2008), Stroke rehabilitation reaches a threshold. *PLoS Computational Biology*]

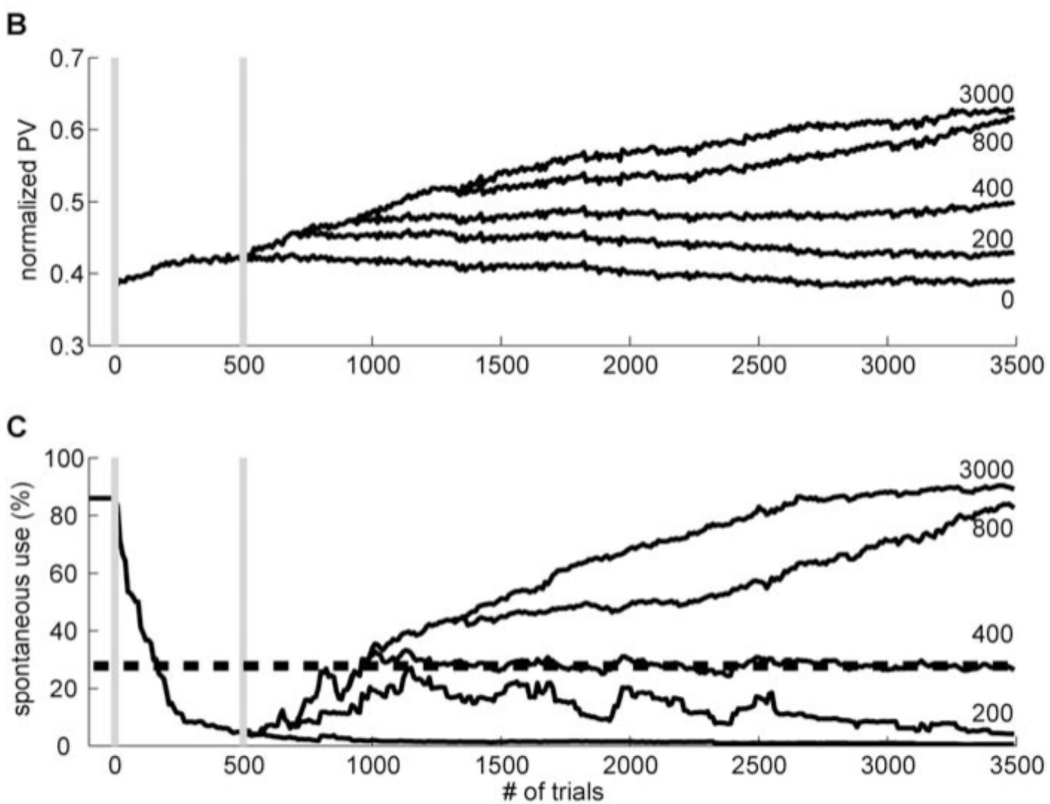
Prediction of preferred arm during recovery

- neural reorganization
- change in spontaneous arm use with and without therapy



[Han et al. (2008), Stroke rehabilitation reaches a threshold. *PLoS Computational Biology*]

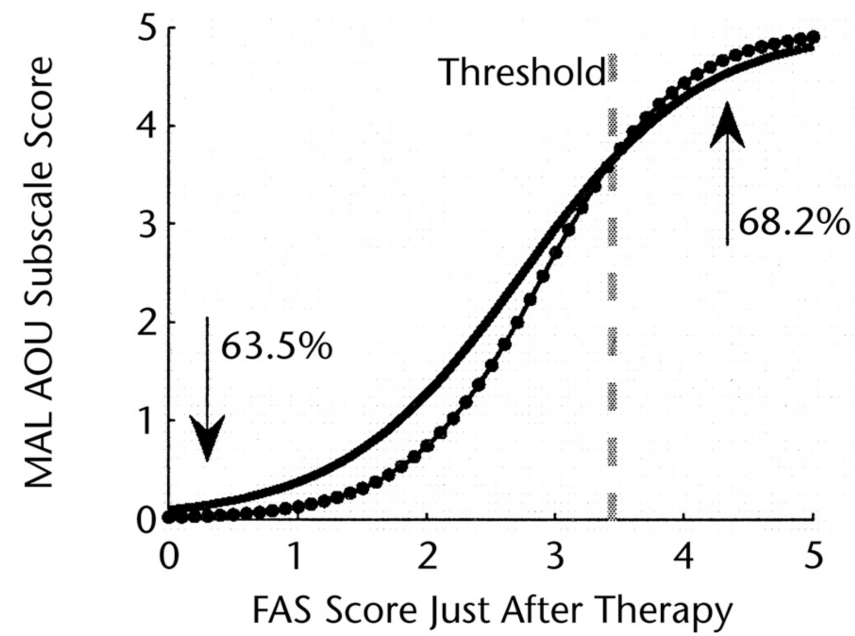
Prediction of preferred arm during recovery



- spontaneous use of affected arm above a threshold: use reinforced after therapy
- below this threshold: compensatory movement reinforced
- sufficient therapy can help patients achieve this threshold

[Han et al. (2008), Stroke rehabilitation reaches a threshold. *PLoS Computational Biology*]

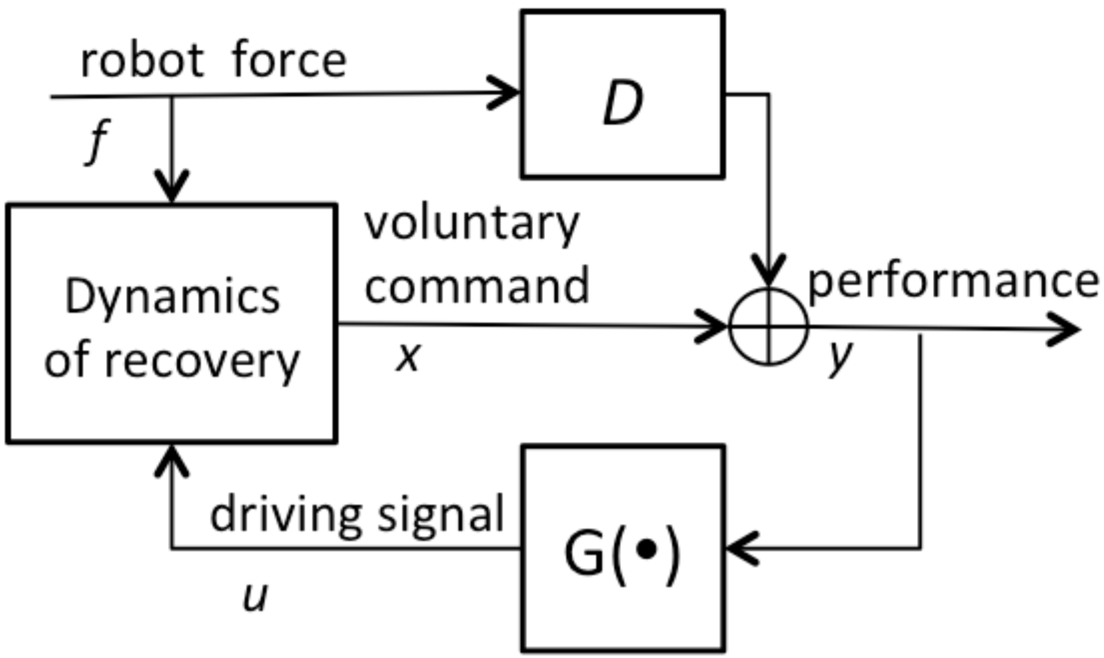
Prediction of preferred arm during recovery



- verification of model predictions with data from constrained induced therapy
- sigmoidal fit between how much a subject uses his affected UE versus how much s/he can use it
- intersection between sigmoids from just after therapy and one year follow up provides a threshold for continue improvement.

[Schweighofer et al. (2009), A functional threshold for long-term use of arm can be determined. *Physical Therapy*]

Linear state space model of recovery after stroke



observation equation:

$$y(i) = x(i) + Df(i)$$

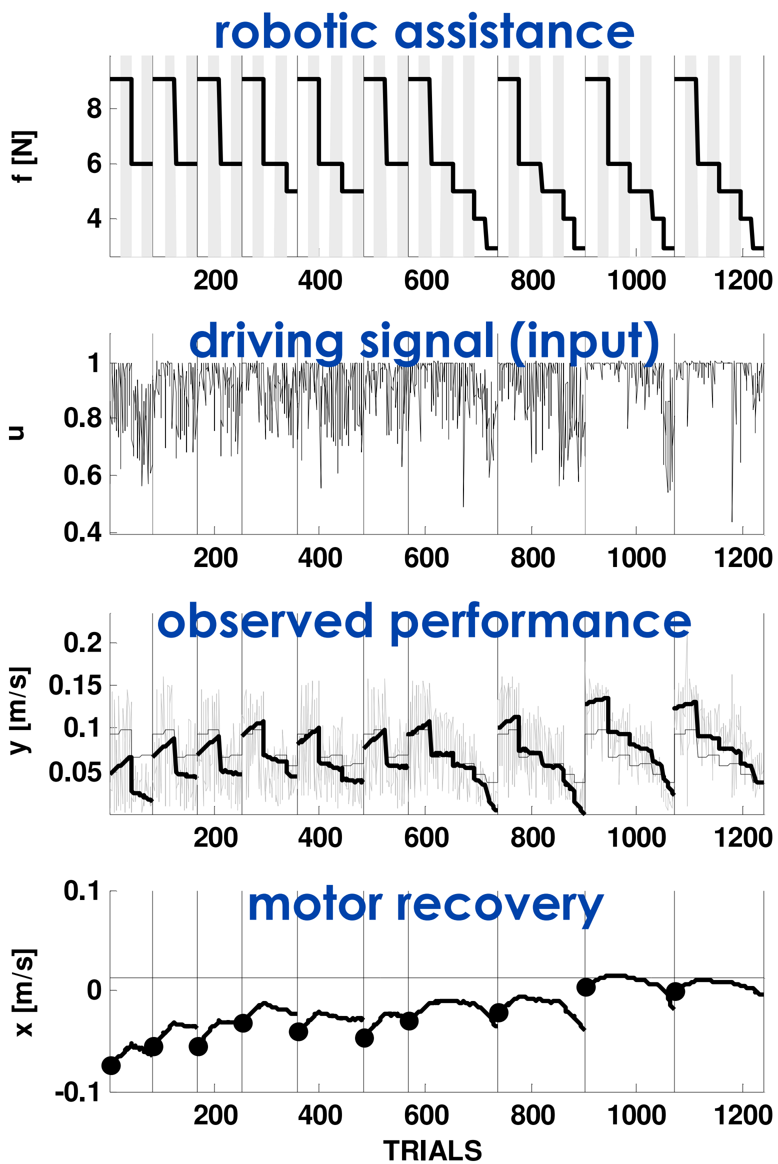
state equation:

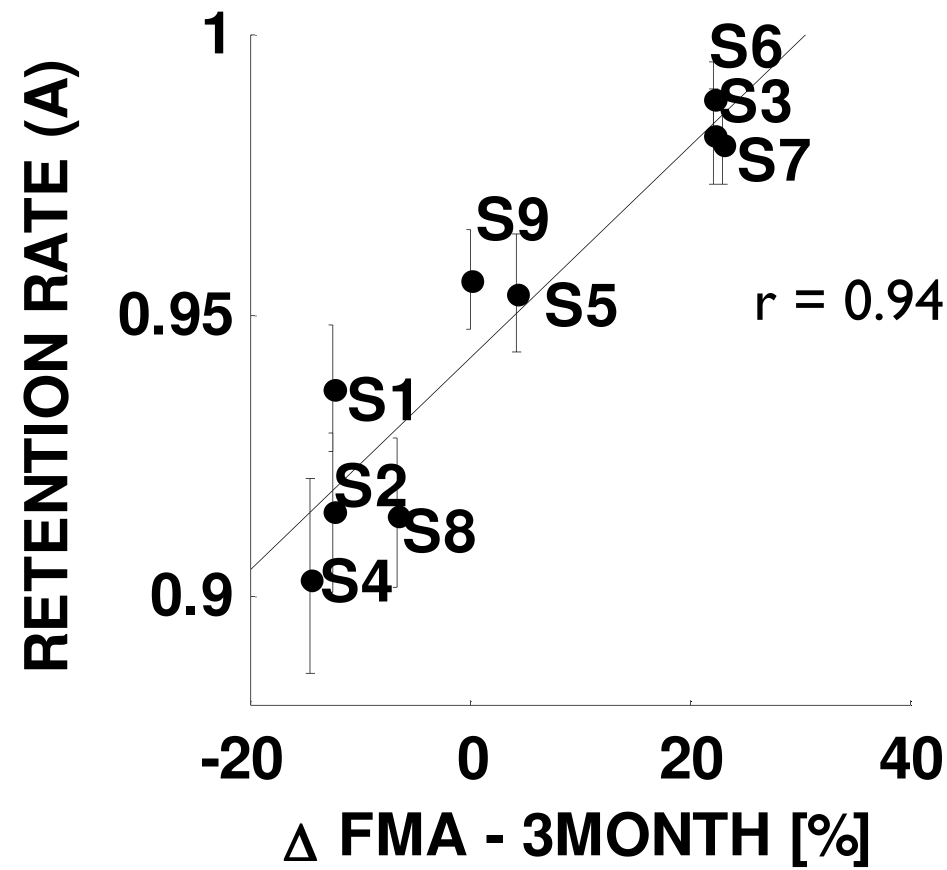
$$x(i+1) = Ax(i) + Bu(i) - Sf(i)$$

- evolution of measured performance *y* over the course of therapy
- motor recovery is modelled as a state variable *x* estimated from movement performance
- minimise assistance

[Casadio and Sanguineti (2012), A model of the dynamics of recovery in robot therapy, *IEEE TNSRE]*

Linear state space model of recovery after stroke



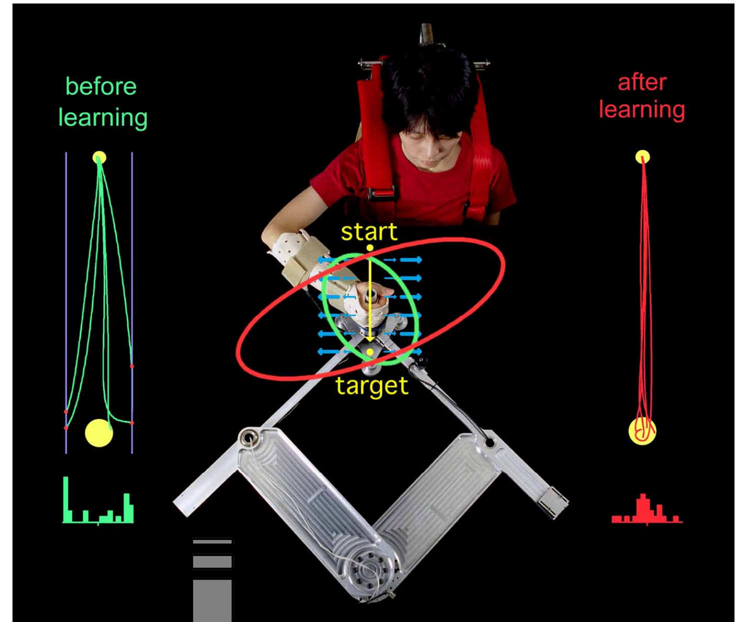


retention rate A predicts the improvement of motor function

Discussion

- only two models!?
- no one of them enables you to develop an optimal protocol or to provide optimal assistance with a robot
- Schweighofer’s model predicts a threshold to reach with rehabilitation, but may be biased towards constrained induced therapy and has large error rate
- Casadio&Sanguineti’s model can predict long-term recovery
- MIMO models might provide a comprehensive picture of the underlying recovery construct

BRAIN CORRELATES OF MOTOR FUNCTION



- how the brain controls motion and adapts to computer-controlled environments
- robotic interface to observe the changes in brain activity during learning/rehabilitation using fMRI

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

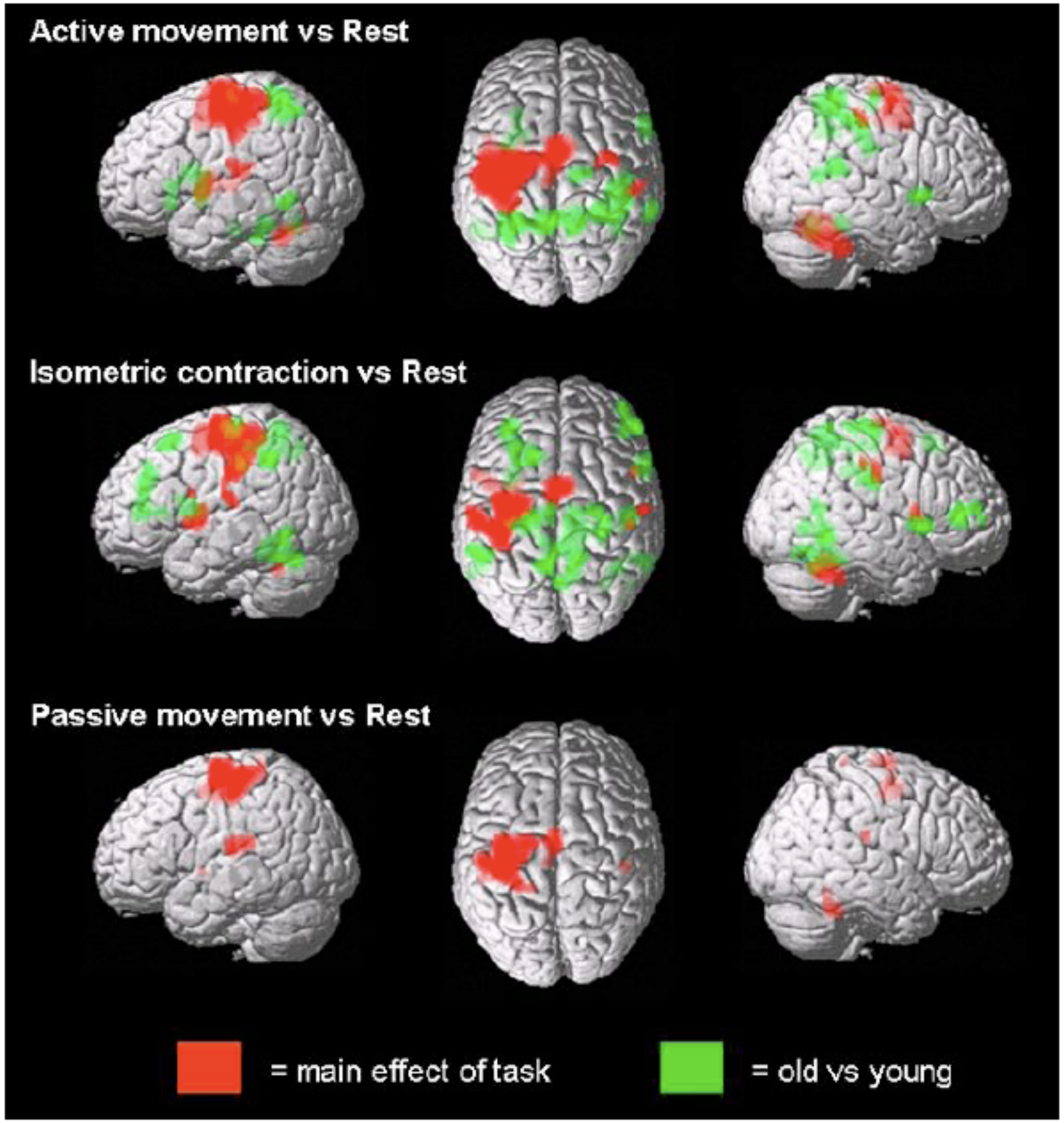
[Gassert et al. IEEE TMECH 2006, IEEE EMBS 2008]

BRAIN CORRELATES OF MOTOR FUNCTION

- old versus young subjects
- 4 conditions: active, passive, isometric, rest
- feedforward = active-passive = isometric-rest
- feedback = active - isometric = passive - rest

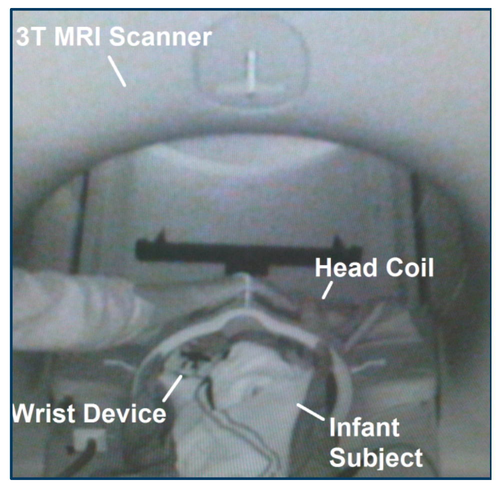
BRAIN CORRELATES OF MOTOR FUNCTION

- old subjects need more activation to perform actions
- but young and old perform similar
- do old subjects use larger brain areas as a compensatory strategy?



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

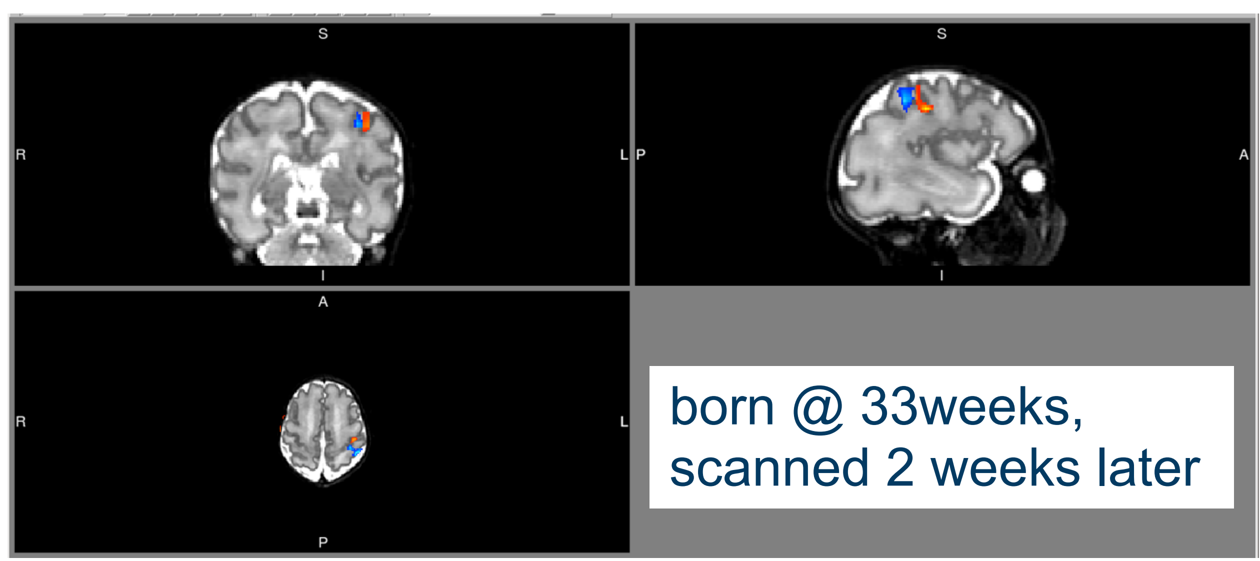


SENSORI-MOTOR ACTIVITY IN PRETERM INFANTS

- 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

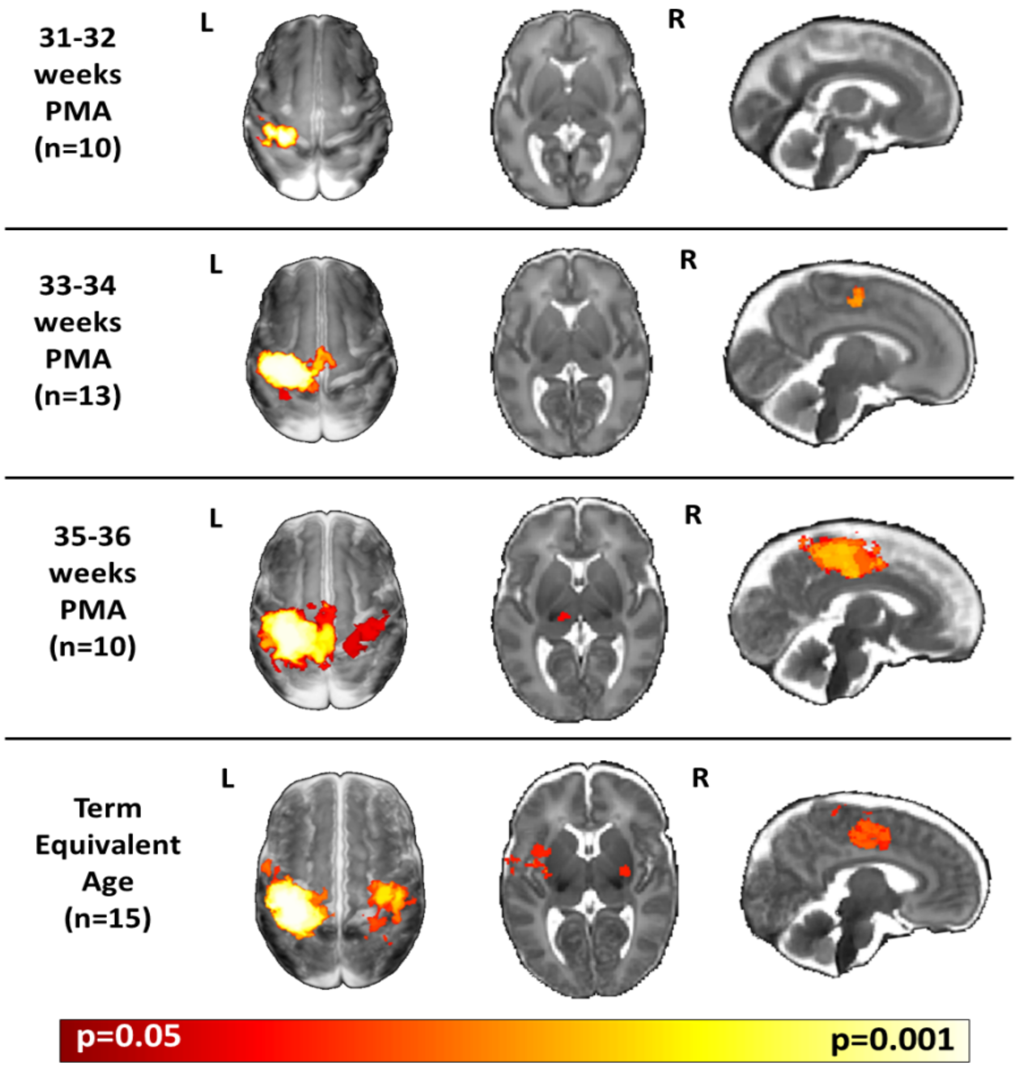
active results cluster in primary motor cortex



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

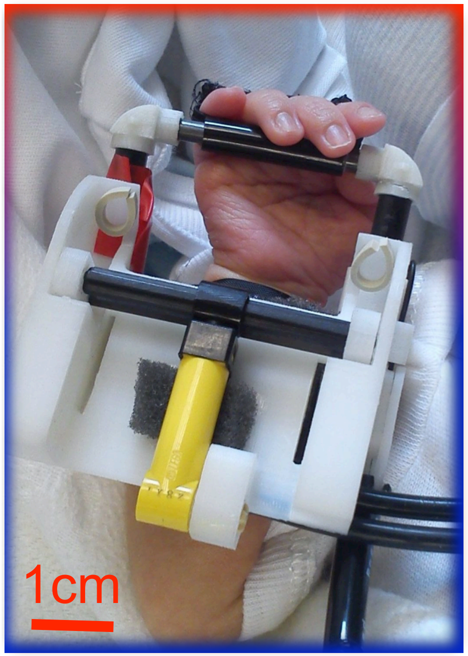
The sensory-motor activity develops in the last trimester

- increasingly complex functional responses are seen as infants mature
- there is increasing involvement of accessory areas and the ipsilateral hemisphere
- this is likely to be associated with increasing growth of structural connections
- overall response decreases at term



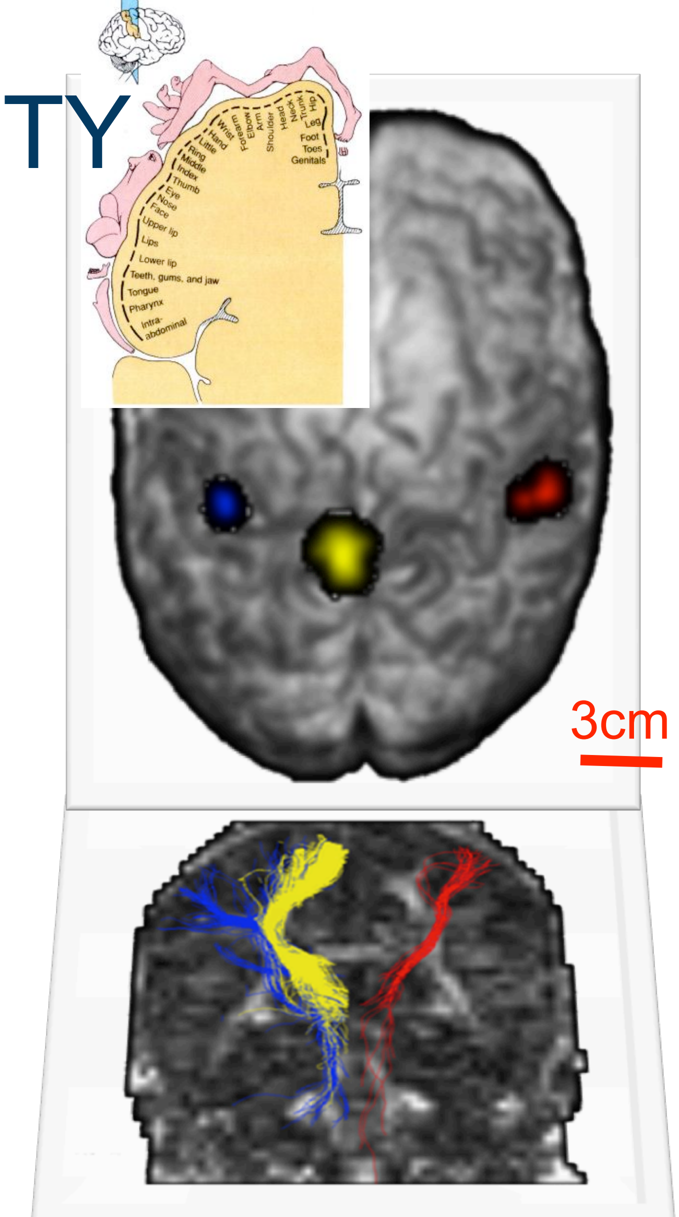
Allievi et al. 2015 Cerebral Cortex

SENSORI-MOTOR ACTIVITY IN PRETERM INFANTS



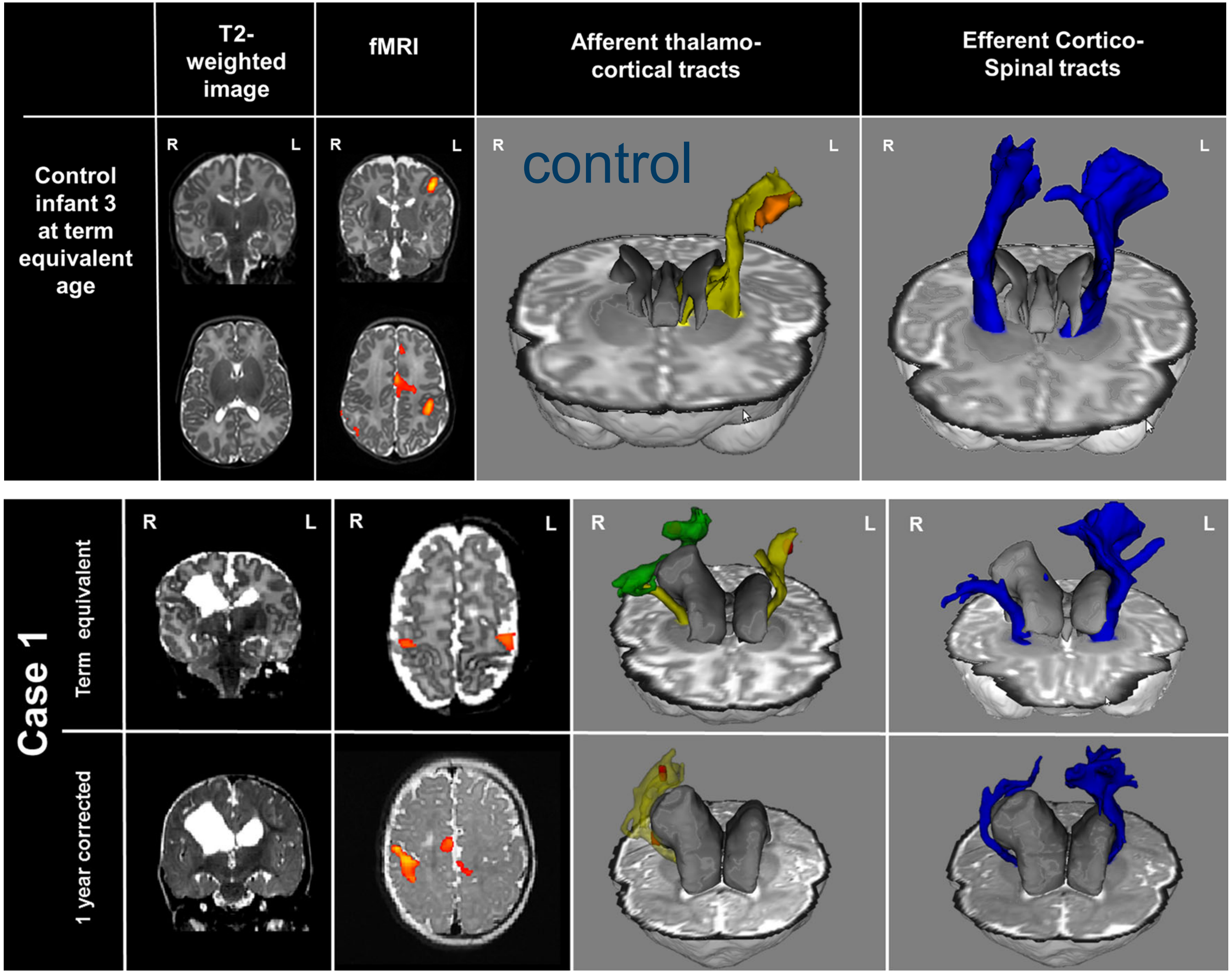
right/left wrist interface

right ankle interface



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

Alterations of structural and functional connectivity in the sensorimotor system of infants with perinatal brain injury



marked asymmetry in the efferent corticospinal tracts, with a decreased volume in the lesional hemisphere

altered trajectories circumvent the periventricular white matter lesion to meet the fMRI clusters

Arichi et al. 2014 Neuroradiology

NEUROSCIENCE OF REHABILITATION

- design simplified by considering motor control factors
- experiments with healthy subjects learning a novel task to develop strategies for rehabilitation
- computational neurorehabilitation: models of motor recovery after stroke
- to investigate neural structures and processes involved in rehabilitation

- profit from the sensorimotor and social benefits of the interaction
- patient and therapist can succeed together, and both of them are challenged so interested in playing i.e. training