COLLABORATIVE ROBOTS FOR MOBILITY ASSISTANCE AND REHABILITATION

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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

Lokomat for walk neuro-rehabilitation @ Hocoma

microsurgery training at NUS
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
human-machine interaction

human motor control

computational neuroscience

feedback error learning decay

feedforward controller

planned trajectory

reflex

noise

robot-assisted rehabilitation

virtual reality based surgery training

assistive devices
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

• 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

- 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 → muscle & reflexes → arm & task dynamics → actual movement

motor command → feedback

change of muscle activation

[Franklin et al. 2008 J Neuroscience]
LEARNING MODEL

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

change of muscle activation

[Franklin et al. 2008 J Neuroscience]
LEARNING: FROM HUMAN TO ROBOT

position
force
stiffness

[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

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

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

• 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
• 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

• 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 Arm/Hand Function to Quadriplegic Quality of Life

To most appropriately assess the priorities of the SCI population, the responses were grouped into quadriplegics and paraplegics. For quadriplegics, as shown in Figure 1A, 48.7% of the participants indicated that regaining arm and hand function would most improve their quality of life and another 11.5% ranked increased upper body/trunk strength and balance as most important. Thirteen percent ranked sexual function to be the priority while 8.9% regarded bladder/bowel function and the elimination of autonomic dysreflexia to be more important. The latter is a life-threatening condition defined by a sudden and severe increase in blood pressure and simultaneous decrease in heart rate induced by a noxious stimulus below the level of injury; individuals with a T6 injury or above are at risk of developing autonomic dysreflexia. Regaining walking movement was the highest priority to only 7.8%, followed by regaining normal sensation (6.1%), and eliminating chronic pain (4%).

Importance of Sexual Function to Paraplegic Quality of Life

For the paraplegic participants, 26.7% ranked regaining sexual function to be the most important to quality of life (Fig. 1B). This was followed by improving bladder/bowel function and eliminating autonomic dysreflexia (18%) and increasing upper body/trunk strength and balance (16.5%). Regaining walking movement was ranked higher by paraplegics (15.9%) than by quadriplegics (see above), as was eliminating chronic pain (12%). Regaining normal sensation (7.5%) and improving arm/hand function (3.3%) were regarded as the least important to improving the quality of life of paraplegics.

Both Quadriplegics and Paraplegics Share Similar Priorities When Ranking Bladder/Bowel and Sexual Function as the First or Second Most Important Factor Affecting Quality of Life

Similar priorities were chosen by quadriplegics and paraplegics when the first and second ranked functions were combined. To perform this analysis, the number of people (quadriplegics and paraplegics were analyzed separately) who ranked a particular function as the first priority were combined with the number of people who ranked that same function as the second priority. Because of the differences in the most important recovered function indicated by quadriplegics versus paraplegics (arm/hand function versus sexual function), this analysis was performed in order to assess functions that were important to both groups. Regaining bladder/bowel function and eliminating autonomic dysreflexia was the first or second highest priority for 39.7% of quadriplegics and 38% of paraplegics (Fig. 2). Similarly, regaining sexual function was the first or second highest priority to 28.3% of quadriplegics and 45.5% of paraplegics. Regaining walking movement, however, was ranked differently between the two groups, with 14.2% of quadriplegics and 38.1% of paraplegics ranking it as the first or second most important function to improve quality of life.

[Anderson J Neurotrauma 2004]
ARM ROBOTS WITH HAND MODULE

MIT-Manus

ARMin (ETHZ)

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

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

[Lambercy et al. 2011 Journal of NeuroEngineering & Rehabilitation]
HAPTIC KNOB: PRONOSUPINATION GAME

- score = $f(\text{adjustment time})$
- automatic adaptation of difficulty level with increase of resistance and required precision

[Lambercy et al. 2011 Journal of NeuroEngineering & Rehabilitation]
HAPTIC KNOB: CHRONIC PATIENTS TRIAL

**hand closing**

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

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

**forearm rotation**

[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£

cost, complexity, need for assistance

complex robots

100’000-1’000’000£

dsafety, 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)
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
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 @ 33 weeks, scanned 2 weeks later

[Allievi et al. 2013 IEEE T. Biomedical Engineering]
SENSEORY 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]
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 infant 3 at term equivalent age

Preterm infant with stroke

Control infant at term equivalent age

Preterm infant

[Arichi et al. 2014 Neuroradiology]
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KINEASSIST @ KINEADESIGN

- 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

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

[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
EUROHAPTICS 2016

The premier European event in haptics

July 4-7, 2016
Imperial College
London, UK

Haptics science & technology, exhibition
near Museums and Hyde Park

www.eurohaptics2016.org