Robots for Neurorehabilitation and Assistance of Gait

Prof. Dr.-Ing. Robert Riener
Sensory-Motor Systems Lab
Institute of Robotics, ETH Zurich
University Hospital Balgrist, University of Zurich
SMS Lab: 2 Affiliations, 2 Locations

ETH Zurich
Institute for Robotics and Intelligent Systems

University Hospital Balgrist
Spinal Cord Injury Center
Patient Activity: Swiss Clinics

less than 2 hours per day => less than 6 % motion therapy

Kool, Wieser, Brügger, Dettling. Entwicklung eines Patientenklassifikationssystems (PCS) für die Rehabilitation in der Schweiz, ZHAW, 2009
Patient Activity

More than 90% of the time inactive

www.fokus.de
Children Activity

Infants Practice a Lot

- 0 to 12 month-olds are about 33% of their time active (estimated from Iglowstein et al. 2003)
- 12 to 19 month-olds perform about 420’000 million steps in a month when learning to walk (Adolph et al. 2012)
Disadvantage of Manual Training

For the Therapist
- Physically exhausting
- Ergonomically inconvenient

For the Patient
- Limited training duration
- Gait pattern not optimal

SCI Center, Balgrist University Hospital, Zurich
Current Robotic Platforms for Neurorehabilitation
Gait Rehabilitation "Robots"

GaitTrainer

Lopes

Alex

G-EO

Lokomat

Autoambulator

Haptic Walker

Alex
Robot-Aided Gait Training

Lokomat

G. Colombo
V. Dietz

Balgrist, Hocoma AG
Robot-Aided Gait Training

Lokomat with 7 Degrees of Freedom
Robot-Aided Gait Training

How a Future Lokomat Could Look Like!?

1. Body weight support system
2. Pelvis module
3. Exoskeleton
4. Footplates

G. Colombo (Hocoma AG), A. Luft (University of Zurich); R. Riener (ETH Zurich), H. Vallery (TU Delft, ETH Zurich)
Robot-Aided Gait Training
Human-Robot Cooperation

Increase Intensity

- Duration x frequency
Human-Robot Cooperation

Increase Intensity

- No. of repetitions
Human-Robot Cooperation

Increase Intensity

- No. of repetitions
- Physical effort
  - Strength
Active vs Passive Movements

MR-Compatible Stepper

Collaborations: R. Riener, S. Kollias, V. Dietz
Active vs Passive Leg Movements

1 Healthy Subject, 21 s stepping

Contrast active leg movements versus rest

Contrast passive leg movements versus rest

→ Stronger activations during active movements

Collaboration: S. Kollias, V. Dietz
Human-Robot Cooperation

Increase Intensity

• No. of repetitions

• Physical effort
  - Strength
  - Assist as needed
Assist-as-Needed (AAN) with SCI Mice

Animals
• 27 mice, 14 days post SCI

Training
• Admin of serotonin agonist
• 30 sessions 10 min each
  (6 weeks, 5 per week)

Three Control Strategies
• Fixed movement
• AAN training with different hindlimb coordinations

Results
• AAN with window paradigm shows highest level of recovery with respect to step number, periodicity and consistency.
Mechanical Interaction

Path Control

• Robot behaves assistive, corrective or transparent, when needed

• Free timing for patient

• Support patient, but do not restrict patient

Duschau-Wicke, Vallery, Riener, et al.
Path Control Increases Participation

Heart Rate

Muscle Activity

11 incomplete SCI subjects
Path Control Enhances Variability

“Repetition without Repetition” (Bernstein)
RIC Single Case Study

Subject
• 52 year old male
• Right sided stroke
• 7 months post-stroke

Lokomat Training
• 12 training sessions (4 weeks, 3 per week)

Krishnan et al. 2012
RIC Single Case Study: Results

Training Improves Ankle Tracking Kinematics

Improvement of ankle tracking performance

Reduction of ankle kinematic variability

Krishnan et al. 2012
# RIC Single Case Study: Results

Training Improves Clinical Outcome

<table>
<thead>
<tr>
<th>Performance Variable</th>
<th>Pre-training</th>
<th>Post-training</th>
<th>Follow-up</th>
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<tbody>
<tr>
<td>TUG</td>
<td>14 s</td>
<td>11 s</td>
<td>11 s</td>
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<tr>
<td>6-min Walk</td>
<td>228 m</td>
<td>316 m</td>
<td>304 m</td>
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<tr>
<td>Single-Leg Balance</td>
<td>1 s</td>
<td>15 s</td>
<td>14 s</td>
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<tr>
<td>Self-Selected Gait Velocity</td>
<td>0.72 m/s</td>
<td>1.0 m/s</td>
<td>0.85 m/s</td>
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<tr>
<td>Fast Gait Velocity</td>
<td>1.1 m/s</td>
<td>1.3 m/s</td>
<td>1.3 m/s</td>
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<td>LE Fugl-Meyer</td>
<td>16</td>
<td>20</td>
<td>23</td>
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</tbody>
</table>

Krishnan et al. 2012
RIC Single Case Study: Results

Improvements Are Substantially Larger

• than mean improvement seen after *conventional Lokomat* (i.e. position-controlled) assisted gait therapy and
• than manual therapist-assisted *treadmill training*

Hornby et al. 2008; Westlake & Patten 2009; Husemann et al. 2007; Plummer et al. 2007

Results Could Be Repeated with a 2\textsuperscript{nd} Case

Krishnan et al. 2013 (Archives of PM&R)

Clinical Trials with Cooperative Training Modes Required
Motivation During Gait Training

Conventional Training

Can be monotonous and boring
Human-Robot Cooperation

Increase Intensity

- No. of repetitions
- Physical effort
  - Strength
  - Assist as needed
Human-Robot Cooperation

Increase Intensity

- No. of repetitions
- Physical effort
  - Strength
  - Assist as needed
- Mental effort
  - Task & difficulty
  - Motivation & reward
Gait Training & Virtual Reality

Collaboration: Children Hospital Affoltern, Hocoma, ZHDK
Engagement Increases Neuroplasticity

Engagement

- Physical activity
- Mental activity

Increased neuroplastic effects
Yerkes-Dodson’s Law

- Weak engagement
- Optimal engagement
- Exhaustion

Performance vs. Engagement

- Low (Underaroused): Poor Performance
- Moderate (Optimally aroused): Maximum Performance
- High (Overaroused): Poor Performance
Audiovisual Scenarios

Increasing Arousal
Control Mental Engagement

Biomechanical Control Loop

State Estimator
- Linear Discriminant Analysis
- Kalman Filtering

Audiovision
- Audiovisual Scenery
- Task Difficulty
- Biomechanics

Position & Force Sensors

Robot & Treadmill

Task Performance

Motions & Forces

Physiological Signals
- ECG
- Skin Temp
- GSR
- Breathing

Psychophysiological Control Loop
A. Koenig, R. Riener (ETHZ) & M. Munih, D. Novak (Univ. Ljubljana)
Portable Gait Exoskeletons

Honda | EksoBionics | Cyberdyne | NASA | MIT Exos | Zoss et al., 2006

Rewalk | Rexbionics | Parker | Park et al., 2011 | Wehner et al., 2013 | Raj et al., 2011
Advantages and Disadvantages

Wearing a Rigid Exoskeleton Means ...

- Motion assistance or strong guidance
- Support of body weight
- Enable different motion tasks
- Added mass, inertia, friction
- Limited transparency
- Kinematic constraints
- Bulky device
- Collisions with environment
- Discomfort
Versatile Lower Limb Exoskeleton
A tool to investigate the influence of exoskeleton design characteristics on human-robot interaction
VLEXO: 8 DOF with large ROMs

Passive Device!
<table>
<thead>
<tr>
<th>Design Variables</th>
<th>Effects</th>
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</thead>
<tbody>
<tr>
<td>1. Kinematic contraints</td>
<td>A. Interaction forces between exoskeleton and human</td>
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<tr>
<td>- limited number of DOFs</td>
<td></td>
</tr>
<tr>
<td>- reduced ROM</td>
<td>B. Movement alterations, e.g. at trunk and ankle</td>
</tr>
<tr>
<td>2. Joint axes misalignments</td>
<td></td>
</tr>
<tr>
<td>3. Exoskeleton mass</td>
<td>C. (Dis-)Comfort, pain</td>
</tr>
<tr>
<td>4. Exoskeleton backlash</td>
<td>D. Exoskeleton sensing inaccuracies</td>
</tr>
</tbody>
</table>
Mass Properties

- Low mass of the device
  "maximal 6 kg at the pelvis and 2 kg at the ankle of additional INERTIA → no significant gait alteration in healthy people" (Meulemann et al. 2013)
- Additional mass can be added to investigate effects
Variable Misalignment

\[ F_{\text{mis}} = f(\phi_{\text{joint}}, \delta_{\text{axis}}, x_{\text{cuff}}) \]
Effects on Interaction Forces

1-DOF force sensors at each cuff attachment
Soft vs. Stiff Exoskeletons

**Advantages**
- Less bulky
- Larger ROMs
- Less misalignment
- Lower mass
- Higher comfort

Wyss-Institute, Boston (Asbeck, Alan, Walsh, et al.)
Our Target Scenario
Target Scenario

Target Population
• Elderly and neurological patients with residual muscle function
• Wheelchair users

Target Movements

"Stand up" → "Walk" → "Climb Stairs"
Which Joints?

Simple Design
- Restrict to sagittal plane
- Only 1 active DOF per leg (cable system)
- Exploit joint synergies

Sagittal plane
- Hip joint
- Knee joint
- Ankle joint
- Combination of joints
Walking: Terminal-Stance

Main Joint Actions
- Hip flexion
- Little knee torque
- Ankle plantarflexion

Accelerating Action!
Walking: Loading Response (& MSt)

Main Joint Actions
• Hip extension
• Knee extension
• Little ankle torque

Antigravity Action!
Antigravity vs Accelerating Support

Main Joint Actions
• Hip extension
• Knee extension
• Little ankle torque

Antigravity Action!

Main Joint Actions
• Hip flexion
• Little knee torque
• Ankle plantarflexion

Accelerating Action!
SMS Exosuit - Concept

- MCU
- Actuation Path
- Passive Element
- Tendon Actuator
SMS Exosuit - Concept

MCU

Actuation Path

Passive Element

Tendon Actuator
Stiffness of the Suit-Human-Interface

Textile Architecture

Woven

Knitted

Non-Woven

Textile Materials

Human Anatomy and Tissue
Tendon Actuator

Specifications

Max. force: 700N
Max. cable travel: 24cm
Weight: 650g
Thigh Interface

First Layer: Stiffness
• Carbon, glass fiber and polyamide
• On crucial spots of actuation path
• Entire suit remains soft

Second Layer: Actuation
• Holds actuators
• Guides tendons along the human body
Anchoring Points

Pelvis Anchoring Point

Foot anchoring point
Passive Elements

Passive Antagonists

• Bio-inspired, antagonistic architecture
• Increases joint stability
• Supports hip & knee flexion
SMS Exosuit – Integrated Sensors

Knee and hip joint angles:
String potentiometers

CoM velocities:
Accelerometer

Force change for sit-to-stand:
FSRs (seat switch)

Gait phases:
FSRs
Gyrosopes
MCU and Battery Placement

- MCU
- Batterie compartment
Sit-to-Stand Transfer
Stair Ascent

MAXX: Mobility Assisting Textile Exosuit
CYBATHLON
CHAMPIONSHIP FOR
ROBOT-ASSISTED ATHLETES
WITH DISABILITIES
Paralysed Claire Lomas finishes London Marathon 16 days after it began

32-year-old is greeted by crowds of supporters as she becomes first to finish marathon in bionic suit
«Walk Again» Project, M. Nicolelis et al. FIFA World Cup 2014
65 Million Wheelchair Users Worldwide\textsuperscript{1}

60'000 C-Legs sold till 2015

C-Leg
Otto Bock
Common Prostheses Are Not Actuated
Goal of the Cybathlon

Promote the Development of USEFUL Assistive Systems
... and Remove Barriers between People with Disabilities and the General Public through Research and Development.
Powered Exoskeleton Race
Powered Leg Prosthesis Race
Powered Wheelchair Race
Powered Arm Prosthesis Race
Muscle Stimulation Bike Race
Muscle Stimulation Bike Race

5 rounds

Start 1
Goal 1

Start 2
Goal 2
Brain-Computer Interface Race
Brain-Computer-Interface Race
## Cybathlon: 8 October 2016

### QUALIFICATIONS: Morning

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<tr>
<th>Zeit</th>
<th>BCI Station</th>
<th>FES Bahn</th>
<th>Objektbahnen</th>
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<td>BCI-Q1</td>
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### FINALS: Afternoon

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**LIVE TV**

Abschlussrede
Show bis ca. 19.00
## Registrations: Current State

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Pilots</th>
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<tbody>
<tr>
<td>FES Bike</td>
<td>11 (+3)</td>
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<tr>
<td>Leg Prosthesis</td>
<td>8 (+1)</td>
</tr>
<tr>
<td>Exoskeleton</td>
<td>16 (+2)</td>
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<tr>
<td>Wheelchair</td>
<td>8 (+1)</td>
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<tr>
<td>Arm Prosthesis</td>
<td>7 (+1)</td>
</tr>
<tr>
<td>BCI</td>
<td>15 (+3)</td>
</tr>
</tbody>
</table>

### Actual State (Sept. ‘15)
- 65 (+11) Pilots
- 55 Teams
- 22 Countries:
  - Europe (CH, UK, BE, FR, DE, ES, AT, SW, IS, etc.)
  - North America (US, CA)
  - Latin America (MX, BR)
  - Asia (JP, KO, HK, SP, TH)
  - Australia
Japanese Television Shows

NHK Sakidori, June 2015

NHK News Channel, Oct 2014