Robotic Rehabilitation for Stroke and Spinal Cord Injury

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Mission of the MAHI Lab at Rice

Design, manufacture and test mechatronic or robotic systems to model, rehabilitate, enhance or augment the human sensorimotor control system
Robot-assisted rehabilitation for stroke

- **Stroke statistics**
  - About 800,000 persons annually in the United States suffer a cerebral vascular accident (CVA), or stroke, with the total number of survivors estimated at 6.5 million (AHA website, July 2009)
  - Direct and indirect costs due to stroke are estimated as $68.9 billion for 2009

- **Robotic-assisted rehabilitation offers a number of potential benefits**
  - Therapist can oversee multiple patients simultaneously
  - In-home tele-rehabilitation is possible
  - Quantitative data recorded by robotic device can track patient progress
  - Programmable nature of robotic system enables bespoke treatment
  - Technology motivates patients and improves outcomes
Robotic measures of motor impairment: Motivation

- Benefits of robotic rehabilitation
  - Repetitive movements
  - Controlled delivery
  - Quantitative metrics

- Need for known correlation between robotic measures and clinical measures
Clinical and robotic measures have their own advantages and drawbacks

<table>
<thead>
<tr>
<th>Clinical Measures</th>
<th>Robotic Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficient to compute and evaluate</td>
<td>✓</td>
</tr>
<tr>
<td>Objective measure of performance</td>
<td>✓</td>
</tr>
<tr>
<td>Widely accepted by clinical community</td>
<td>✓</td>
</tr>
<tr>
<td>Independent of task or procedure</td>
<td>✓</td>
</tr>
</tbody>
</table>
A target-hitting task was completed by patients using a haptic joystick.
Four clinical measures administered pre- and post-treatment

- Clinical motor impairment measures
  - Fugl-Meyer (FM) upper-limb component (0-66)
  - Action Research Arm Test (ARAT) (0-57)

- Clinical functional use measures
  - Jebsen-Taylor (JT) Hand Function Test (time in sec)
  - Motor Activity Log (MAL) (0-6)
Four robotic measures of movement quality and movement speed

- Movement quality measures based on minimum jerk principle
  - Trajectory Error (TE)
  - Smoothness of Movement (SM)
- Movement speed measures
  - Average target hits per minute
  - Mean tangential speed
Rehabilitation program

- Nine patients
- Three days a week, 4 hours each therapy day
- Hybrid robotic and traditional rehabilitation program
  - 60% traditional constraint induced movement therapy (CIMT) activities
  - 40% robotic therapy
- Four weeks of therapy
- Follow-up session one month after the last session
## Participant characteristics

<table>
<thead>
<tr>
<th>Patient number</th>
<th>Gender</th>
<th>Age (years)</th>
<th>Months since stroke</th>
<th>Side affected</th>
<th>Stroke location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>62</td>
<td>24</td>
<td>R</td>
<td>L BS</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>63</td>
<td>12</td>
<td>L</td>
<td>R BG</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>62</td>
<td>121</td>
<td>R</td>
<td>L MCA</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>65</td>
<td>50</td>
<td>R</td>
<td>L BG and T</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>48</td>
<td>20</td>
<td>L</td>
<td>R MCA</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>67</td>
<td>14</td>
<td>R</td>
<td>L IC</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>57</td>
<td>25</td>
<td>L</td>
<td>R BG</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>66</td>
<td>77</td>
<td>L</td>
<td>R Pons</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>57</td>
<td>13</td>
<td>L</td>
<td>R IC</td>
</tr>
</tbody>
</table>

**Abbreviations:**
- BS: BRAIN STEM
- HEM: HEMMORHAGIC
- MCA: MIDDLE CEREBRAL ARTERY
- BG: BASAL GANGLIA
- IC: INTERNAL CAPSULE
- T: THALAMUS
Correlations of clinical and robotic measures

- Movement quality measures strongly correlated with motor impairment measures

Correlation coefficient $r$ is listed.
* denotes significant correlation ($p<0.05$)

<table>
<thead>
<tr>
<th></th>
<th>TE</th>
<th>SM</th>
<th>HPM</th>
<th>MTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM</td>
<td>-0.74*</td>
<td>0.64*</td>
<td>0.54*</td>
<td>0.22</td>
</tr>
<tr>
<td>ARAT</td>
<td>-0.83*</td>
<td>0.51*</td>
<td>0.37</td>
<td>0.00</td>
</tr>
<tr>
<td>JT</td>
<td>0.63*</td>
<td>-0.49*</td>
<td>-0.53*</td>
<td>-0.32</td>
</tr>
<tr>
<td>MAL</td>
<td>-0.49*</td>
<td>0.57*</td>
<td>0.46</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Movement quality measures strongly correlate with motor impairment measures

- Trajectory error and smoothness of movement measures can be used for:
  - estimation of clinical measures (additional data needed for validation)
  - adjustment of robotic therapy online based on patient’s progress
  - comparison of different protocols/devices

(Celik et al, IEEE ICRA 2008)
(Celik et al, IEEE TNSRE 2010)
Upper Limb Robotic Rehabilitation for SCI

- Tetraplegia is the most frequent neurologic category reported to the SCI Model Systems
- Repeated practice can induce brain and spinal plasticity and result in significant UL improvements
- No established methods exist for delivering UL repeated practice to persons with SCI
- Upper limb function is a significant factor in quality of life after tetraplegia
- Robotic devices can help therapists deliver repeated practice
- Clinical evaluation can provide guidance to the community
Aims

• Describe the design features of the RiceWrist and MAHI-Exo-II devices
• Confirm the feasibility of using these devices for upper limb training in tetraplegic persons with incomplete SCI
• Detect motor progress using robotic and clinical measures
MAHI exo and RiceWrist Evolution

Gupta and O’Malley, ASME/IEEE TMECH 2006
Gupta et al., IJRR 2008
Pehlivan et al., ICORR 2011
Kadivar et al., ICORR 2011
RiceWrist evaluation: Participant

- 24-year-old male
- Incomplete SCI at C4
- 6.5 months post-injury
- ASIA D according to American Spinal Injury Association Impairment Scale
- Minimum voluntary movement on the weaker right upper limb
- Moderate level of voluntary movement on the stronger left limb
RiceWrist evaluation: Training

- Three hours per day, 10 consecutive weekdays for the right and left upper limbs
- Sessions customized using passive, active constraint and triggered modes
- Collected measures:
  - Smoothness factor (Fs)
  - Jebsen Taylor Hand Function Test
<table>
<thead>
<tr>
<th>Jebsen-Taylor Hand Function Subtest</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated page turning (5 cards)</td>
<td>n/a</td>
<td>11.82</td>
</tr>
<tr>
<td></td>
<td>150(5)</td>
<td>7.09</td>
</tr>
<tr>
<td>Lifting small common objects (2 paper clips, bottle cap, pennies, cup).</td>
<td>n/a</td>
<td>20.88</td>
</tr>
<tr>
<td></td>
<td>180(2)</td>
<td>20.44</td>
</tr>
<tr>
<td>Simulated feeding (5 kidney beans)</td>
<td>n/a</td>
<td>17.53</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>15.25</td>
</tr>
<tr>
<td>Stacking checkers (4 checkers)</td>
<td>n/a</td>
<td>44.13</td>
</tr>
<tr>
<td></td>
<td>180(2)</td>
<td>20.03</td>
</tr>
<tr>
<td>Lifting large light objects (5 cans)</td>
<td>n/a</td>
<td>6.87</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>5.87</td>
</tr>
<tr>
<td>Lifting large heavy objects (5 cans)</td>
<td>180(2)</td>
<td>6.85</td>
</tr>
<tr>
<td></td>
<td>180(4)</td>
<td>6.28</td>
</tr>
</tbody>
</table>
Results: Smoothness Factor

Angular Velocity (1/s)

Pre-training

Forearm-Pronation

F_s=0.16

Post-training

F_s=0.54

Time (s)

Minimum Jerk Velocity

Best Fit Curve

Subject Velocity
Results: Smoothness Factor

Average Smoothness Left UL

Data from Sessions 2 and 10 were used for pre- and post-assessment.
MAHI Exo II evaluation: Participant

- 28-year-old female
- Incomplete SCI at C2
- 29 months post-injury
- ASIA C according to American Spinal Injury Association Impairment Scale
- Minimum voluntary movement on the weaker right upper limb
- Moderate level of voluntary movement on the stronger left limb
MAHI Exo II evaluation: Training

• Three hours per session, 12 sessions over four weeks
• Sessions customized using passive, active constraint and triggered modes
• Performance measures:
  – Smoothness factor (Fs)
  – ASIA
  – ARAT
  – Jebsen Taylor Hand Function Test
Functional scores before and after robotic-assisted training

ASIA: American Spinal Injury Association, ARAT: Action Research Arm Test, JTHFT: Jebsen Taylor Hand Function Test. The JTHFT was ended after 180sec. Lower times represent better performance.

<table>
<thead>
<tr>
<th>Task</th>
<th>Side</th>
<th>Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASIA – upper extremity motor score (0-25)</td>
<td>Right</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>ARAT (0-57)</td>
<td>Right</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>41</td>
<td>49</td>
</tr>
<tr>
<td>JTHFT (total time in seconds)</td>
<td>Right</td>
<td>1080</td>
<td>1080</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>151.64</td>
<td>80.4</td>
</tr>
</tbody>
</table>
Angular velocity profiles pre- and post- treatment

(A/B) forearm supination

(C/D) wrist radial deviation

(D/E) wrist extension
MAHI Exo II Evaluation
MAHI Exo II Evaluation
MAHI Exo II Evaluation
Summary of Results

• Subjects are able to successfully complete multiple sessions of robot-assisted training with RiceWrist and MAHI Exo II
• Kinematic performance measures show mixed results, but analysis incomplete
  – Large improvements in movement smoothness observed for left upper limb
  – No observed improvements in movement smoothness for right upper limb
• Clinical performance measures capture some UL improvements
Mechanisms of recovery

• Reorganization of remaining neural circuits
• Formation of new circuits at cortical and sub-cortical regions including the spinal cord below the lesion
• Minimum improvements for right upper limb (the weaker limb) suggestive of longer or combined forms of therapy?
• Spontaneous recovery cannot be ruled out
Conclusions

- Robotic devices can potentially play an important role in the rehabilitation of distal degrees of freedom of the upper limb after SCI
- Robotic devices as assessment tools can generate valuable objective measures
- Potential exists for customized and performance-based therapeutic strategies
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http://mahilab.rice.edu

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