Exoskeletal Assisted Walking: Training Methods and Mobility Skills Achieved

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Support

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Presentation Overview

- Brief history of assisted ambulation
- Basics of Powered Exoskeletons
- Training with the powered exoskeleton
- Initial Research
  - Walking Measurements
  - Vertical ground reaction forces during exoskeletal-assisted walking
  - Heart Rate and Oxygen Demand of Powered Exoskeleton-Assisted Walking
Brief review of Walking Technologies for Persons with Paraplegia

**Reciprocating Gait Orthosis (RGO)**


**Functional Electrical Stimulation (FES)**

RGO Walking Video
EXOSKELETONS
Early Exoskeletons

Yagn’s Running Aid
(Yagn, 1890)

GE’s Hardiman
(Fick & Mackinson, 1971)

BLEEX
(Kazerooni & Steger, 2006)

Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art
Current Exoskeleton Systems for Persons with SCI
Weighs 50lbs (23kg)

Variable Assistance

Motorized Hip and Knee Joints

Backpack with 2 rechargeable batteries and electronic control system

Motorized Hip and Knee Joints
FirstStep™
A physical therapist actuates steps with a button push. The user progresses from sit to stand and using a walker to walking with crutches, often in their first session.

ActiveStep™
User take control of actuating their steps via buttons on the crutches or walker.

ProStep™
The user achieves the next step by moving their hips forward and shifting them laterally. The Ekso device recognizes that the user is in the correct position and steps.

NEW ProStep Plus™
Steps are triggered by the user’s weight shift PLUS the initiation of forward leg movement.

http://www.eksobionics.com/ekso
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  • Walking Measurements
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Powered Exoskeletal Walking System for Persons With Paraplegia

- ClinicalTrials.gov Identifier: NCT01454570
- 3x / week, 1-2 hours /session
- 4 to 5 months

Outcomes
- Walking tests (10m, Six-min, TUG)
- Mobility skills
- Body composition, bowel function, energy expenditure, and quality of life
Basic Training Goals:

- Fitting device and donning/doffing
- Sit-to-Stand
- Stand-to-Sit
- Standing balance
- Weight shifting
- Walking – Indoor Flat surface
Device Components

- Backpack containing computer and batteries
- Tilt Sensor
- Motors
- Foot Plates
- Communicator
- Pelvic Band
Proficiency and Level of Independence for Mobility Skills

- Donning/doffing the device
Standing up Video
Stand Balance Training
Stand Balance Training

- Stand balance video
The very beginning

- Early training video
Sample of Walking Progression

Week 1

- Video early walking

Week 4

- Video after 4 weeks of training
Sample of Walking Progression

Week 12 (about 40 sessions)

- Video after 12 weeks training
• T1 motor complete walking with min assist
• T1 video independent
• Self-activation of the remote watch
• Stopping on command or at will
Advanced Training Goals:
Mobility Skills in the Exoskeleton

- Increased walking speeds
- Walking - multiple surfaces
- Walking - Outdoors
- Walking - slopped surface
- Walking – timed doors
- Stair Ascent/Descent
• Maneuver to a wall rest
• Retrieving an item from above head
Navigating motorized doors:
- push button electric door, elevator doors or an automatic revolving door.
Walking:
• Indoors on: tile and carpet
• Outdoors on: concrete, pavement, grass, uneven ground surfaces, slopes, curb cutouts, or navigating a curb
Concrete/Pavement
(1.0 mi Road Race)

- Walking on asphalt
Concrete/Pavement
(Outside a Stadium)

- Walking on asphalt
Curb Cut Out

- Walking down a curb
Down Ramp

- Walking up a curb
Stair Climbing Mode

- Video walking up stairs
Curbs
Around the House

- Video house work
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## Baseline Demographic and SCI Characteristics

<table>
<thead>
<tr>
<th>SID</th>
<th>Age (y)</th>
<th>Ht (in)</th>
<th>Wt (lb)</th>
<th>BMI (kg/m²)</th>
<th>DOI (y)</th>
<th>Gender</th>
<th>Ethnicity</th>
<th>LOI</th>
<th>AIS (LEMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34</td>
<td>68</td>
<td>147</td>
<td>22.3</td>
<td>9</td>
<td>male</td>
<td>Cauc.</td>
<td>T4</td>
<td>B, 0</td>
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<tr>
<td>2</td>
<td>49</td>
<td>66</td>
<td>150</td>
<td>24.2</td>
<td>4</td>
<td>male</td>
<td>Cauc.</td>
<td>T10</td>
<td>A, 0</td>
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<tr>
<td>3</td>
<td>44</td>
<td>72</td>
<td>175</td>
<td>23.7</td>
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<td>Asian</td>
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<td>A, 4</td>
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<tr>
<td>4</td>
<td>58</td>
<td>63</td>
<td>144</td>
<td>25.5</td>
<td>1</td>
<td>female</td>
<td>Cauc.</td>
<td>T8</td>
<td>A, 0</td>
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<tr>
<td>5</td>
<td>61</td>
<td>69</td>
<td>160</td>
<td>23.6</td>
<td>14</td>
<td>male</td>
<td>Cauc.</td>
<td>T11</td>
<td>A, 3</td>
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<tr>
<td>6</td>
<td>24</td>
<td>73</td>
<td>165</td>
<td>21.8</td>
<td>5</td>
<td>male</td>
<td>Cauc.</td>
<td>T5</td>
<td>A, 0</td>
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<tr>
<td>7</td>
<td>40</td>
<td>72</td>
<td>190</td>
<td>25.8</td>
<td>2</td>
<td>male</td>
<td>Cauc.</td>
<td>T1</td>
<td>B, 0</td>
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<tr>
<td>8</td>
<td>50</td>
<td>72</td>
<td>220</td>
<td>29.8</td>
<td>6</td>
<td>male</td>
<td>Hisp.</td>
<td>T7</td>
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<td>9</td>
<td>56</td>
<td>69</td>
<td>185</td>
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<td>Cauc.</td>
<td>T9</td>
<td>A, 0</td>
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<tr>
<td>10</td>
<td>37</td>
<td>67</td>
<td>140</td>
<td>21.9</td>
<td>7</td>
<td>male</td>
<td>Afric. Am.</td>
<td>T2</td>
<td>A, 0</td>
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<tr>
<td>Mean</td>
<td>45</td>
<td>69</td>
<td>169</td>
<td>24.6</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>12</td>
<td>4</td>
<td>26</td>
<td>2.5</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Definitions for Level of Assistance

**Moderate / Minimal Assist (MO/MA)**
- FIM $\leq 4$

**Close Supervision (CCG)**
- FIM 5

**No Assist (NA)**
- FIM $\geq 6$
## Number of Sessions to Walk 10 meters

<table>
<thead>
<tr>
<th>SID</th>
<th>LOI</th>
<th>≈ Sessions</th>
<th>Assistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T4 (A)</td>
<td>6 (80*)</td>
<td>No assist / CCG</td>
</tr>
<tr>
<td>2</td>
<td>T10 (A)</td>
<td>12</td>
<td>Close CG</td>
</tr>
<tr>
<td>3</td>
<td>T4 (A)</td>
<td>8</td>
<td>No assist</td>
</tr>
<tr>
<td>4</td>
<td>C5 (C), T8 (A)</td>
<td>4</td>
<td>No assist</td>
</tr>
<tr>
<td>5</td>
<td>T11 (A)</td>
<td>10</td>
<td>No assist / CCG</td>
</tr>
<tr>
<td>6</td>
<td>T5 (A)</td>
<td>7</td>
<td>Min assist</td>
</tr>
<tr>
<td>7</td>
<td>T1 (B)</td>
<td>15</td>
<td>Mod assist</td>
</tr>
<tr>
<td>8</td>
<td>T7 (A)</td>
<td>5</td>
<td>No assist</td>
</tr>
<tr>
<td>9</td>
<td>T9 (A)</td>
<td>15</td>
<td>Mod assist</td>
</tr>
<tr>
<td>10</td>
<td>T2 (A)</td>
<td>12</td>
<td>Min assist</td>
</tr>
</tbody>
</table>

* 1st Participant; experienced start-up, software adjustments and learning curve
Walking Tests (N=10)

10 m Walk Test

- Number of Sessions: 19±4, 28±13
- p=0.177

6 minute Walk Test

- Number of Sessions: 19±4, 33±15
- *p=0.025
Best Walk Test Results in the ReWalk Participants to Date (N=13)

- SIX Minute Walk Test
  - 4 can walk ≥50 m (≥0.14 m/s or 0.31 mph)
  - 5 can walk ≥100 m (≥0.30 m/s or 0.67 mph)
  - 4 can walk ≥200 m (≥0.56 m/s or 1.25 mph)
  - **Best: 231 m (0.64 m/s or 1.43 mph)**

- TEN Meter Walk Test
  - 4 can walk in ≤120 sec
  - 5 can walk ≤60 sec
  - 4 can walk ≤20 sec
  - **Best: 15 sec**
Walking Speeds in Humans

- **Establishing Pedestrian Walking Speeds.**


3.1 mph  
(1.39 m/s)
Walking speeds in Incomplete-motor SCI during the first year of recovery


**Supervised walker** (minimum speed)
- $0.09 \pm 0.01\text{m/s}$

**Indoors with aid/outdoor wheelchair user**
- $0.15 \pm 0.08\text{m/s}$

**Outdoors with aid**
- $0.44 \pm 0.14\text{m/s}$

**Outdoors without aid**
- $0.70 \pm 0.13\text{m/s}$
<table>
<thead>
<tr>
<th>RESULTS</th>
<th>Performs Task</th>
<th>No Assist</th>
<th>With Assist</th>
<th>Not Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Donning/doffing Device</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>transfer in/out</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>chest, thigh, and calf straps</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>feet in/out of shoes</td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Indoor Standing Skills</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>self-activate the remote watch</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>retrieve item from above head</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Indoor Walking Skills</td>
<td>Performs Task</td>
<td></td>
<td>Not Tested</td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------------</td>
<td>---------------</td>
<td>----------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>arrest gait on command</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>maneuver to a wall rest</td>
<td>5</td>
<td>5</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>walk on carpet</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>navigate a push button door</td>
<td>5</td>
<td>5</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>navigate an elevator</td>
<td>5</td>
<td>-</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>navigate a revolving door</td>
<td>5</td>
<td>-</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
## RESULTS

<table>
<thead>
<tr>
<th>Outdoor Walking Skills</th>
<th>Performs Task</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Assist</td>
<td>With Assist</td>
<td>Not Tested</td>
<td></td>
</tr>
<tr>
<td>walk on concrete</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>walk on uneven ground</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>walk up / down a slight slope</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>walk up / down a curb</td>
<td>-</td>
<td>4</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>
Vertical ground reaction force-based analysis of powered exoskeleton-assisted walking in persons with motor-complete paraplegia

Drew B. Fineberg¹, Pierre Asselin¹, Noam Y. Harel¹,²,³, Irina Agranova-Breyter⁴, Stephen D. Kornfeld⁵, William A. Bauman,¹,³,⁶,⁷, Ann M. Spungen¹,³,⁶,⁷

- Participants
  - 3- Motor Complete SCI w/ Assistance
  - 3- Motor Complete SCI w/o Assistance
  - 3- AB control

F-Scan set up
vGRFs During Stance Phase

Fineberg et al., JSCM 2013
Heart Rate and Oxygen Demand of Powered Exoskeleton-Assisted Walking in Persons with Paraplegia

Pierre Asselin, MS¹, Steven Knezevic, MS¹, Stephen Kornfeld, DO¹,², Christopher Cirnigliaro, MS¹, Irina Agranova-Breyter, PT³, William A. Bauman, MD¹,⁴, Ann M. Spungen, EdD¹,⁴
Oxygen Uptake During Use of the ReWalk

% VO₂R Legs
24±4%

% VO₂R Arms
35±7%

Asselin P, et.al. (under review)
Heart Rate Response During Use of the ReWalk

%HRR 48±16%  
p<0.001

Asselin P, et.al. (under review)
Velocities (6minWT) during metabolic test and during training

Metabolic Test
With Mask

During Training
With Out Mask

P<0.001

Velocity (m/s)

mean=0.22±0.11

mean =0.27±0.11
Current options for SCI over ground ambulation

- Long leg braces
- Hip-knee-ankle-foot orthosis (HKAFO) which includes reciprocating gait orthosis (RGO), Hip guidance orthosis (HGO) and advanced reciprocating gait orthosis (ARGO)
Video of ReWalk and RGO

- Video RGO walking
- VS Video of same person walking in the rewalk
## Energy Expenditure Studies Using RGOs

<table>
<thead>
<tr>
<th>Series</th>
<th>N</th>
<th>VO₂ (ml/kg/min)</th>
<th>Gait velocity (m/s)</th>
<th>Lesion Level</th>
<th>Orthosis</th>
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</thead>
<tbody>
<tr>
<td>Kawashima et. al. [23]</td>
<td>10</td>
<td>18.2±3.8</td>
<td>0.33±0.10</td>
<td>T5-12</td>
<td>ARGO</td>
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<tr>
<td>Winchester et. al. [25]</td>
<td>4</td>
<td>14.2±1.8</td>
<td>0.21±0.03</td>
<td>T5-10</td>
<td>RGO</td>
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<tr>
<td>Bernardi et. al. [24]</td>
<td>10</td>
<td>13.3±3.7</td>
<td>0.26±1.6</td>
<td>T4-12</td>
<td>RGO</td>
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<tr>
<td>Felici et. al. [26]</td>
<td>6</td>
<td>14.3±4.7</td>
<td>0.15±0.08</td>
<td>T5-L1</td>
<td>RGO, ARGO</td>
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<tr>
<td>Massucci et. al. [2]</td>
<td>6</td>
<td>13.7±3.5</td>
<td>0.17±0.05</td>
<td>T3-12</td>
<td>ARGO</td>
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<tr>
<td>Ijzerman et. al. [27]</td>
<td>10</td>
<td>17.6±2.0</td>
<td>0.21</td>
<td>T4-12</td>
<td>ARGO</td>
</tr>
<tr>
<td>Merati et. al. [28]</td>
<td>4</td>
<td>13.4±3.0</td>
<td>0.16±0.01</td>
<td>C7-T8</td>
<td>PW</td>
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<tr>
<td></td>
<td>6</td>
<td>13.8±3.5</td>
<td>0.19±0.03</td>
<td>T3-T11</td>
<td>RGO</td>
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<tr>
<td>Huang</td>
<td>8</td>
<td>11.2±1.4</td>
<td>0.26±.21</td>
<td>T4-T12</td>
<td>CSB</td>
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<td>Present Study</td>
<td>8</td>
<td>11.1±1.7</td>
<td>0.22±0.11</td>
<td>T1-11</td>
<td>ReWalk™</td>
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</table>
Synopsis and Conclusions

- Participants were able to well-tolerate walking for 1 to 2 hours per session, 3x/week (i.e. 4 to 6 hours of walking per week).
- Time in the exoskeleton resulted in improved skill level.
- With improved independence and skill, a more normalized gait pattern is observed and could provide a mechanism for increased loading of the legs.
- Significant increases in HR and VO2, but at a level sustainable for regular use which indicate potential to improve adverse health-related consequences of paralysis, such as adiposity, insulin resistance and lipid profile.
Future areas for Improvement

- Provide postural balance
  - Needed during standing and walking
  - Needs to mimic human-like postural stability and triggering proper reactions
  - Cooperatively move with the robotic exoskeleton
- Improvements in speed
  - Improvements in walking speeds which are closer to uninjured walking (1.4m/s)
  - Walking with ability to vary walking speeds
- Walking environments
  - Up/down slopes
  - Curbs
  - Stairs
Initial findings suggest that after a period of supervised training, most participants could proficiently and independently perform certain home or community-based skills using the exoskeleton.

Further work should identify the amount of training required and the necessary skill level for safe home-, work- or community-specific use of the exoskeletons.
Two Major Reasons to Advance the Field of Exoskeletal-Assisted Walking Technology for SCI

- Health
- Mobility