Quantitative Assessment of Lower Limb and Cane Movement with Wearable Inertial Sensors

Gina Sprint, Diane Cook, Douglas Weeks
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Mobility Impairments

• Functional Independence
  – Age, injury, or disease-related impairments

• Assistive devices
  – Canes, walkers, and wheelchairs
  – Increase base of support
Assistive Devices: Canes

- 16% of adults 65 years and older use a cane
- Used incorrectly
  - 28% of cane users incorrectly hold the cane on their weak side
  - 11% occasionally swing the cane with the ipsilateral leg
  - 14% occasionally hold the cane in the air for multiple steps

Wallace et al. 2015, Liu et al. 2011
Assessing Physical Movement

• Evaluation of motor recovery and physical movement
  – Observation

• Wearable technology for monitoring
  – Fine-grained, objective data
  – Portable, inexpensive, unobtrusive sensors
  – Usage information/insights for users, clinicians, caregivers
Study Design

• 4 Inertial measurement units
  – C: center of mass
  – L/R: left and right shank
  – D: assistive device (cane or walker)

• Ambulatory circuit (AC)
  – 2 Testing sessions (S1 and S2)
  – One week apart

Sprint et al. 2015
AC Study Participants

- N=35 to date, N=2 used cane at S1 and S2

### TABLE I

**PARTICIPANT CHARACTERISTICS**

<table>
<thead>
<tr>
<th>ID</th>
<th>Etiology</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Device</th>
<th>Dominant Side</th>
<th>Affected Side</th>
<th>FIM&lt;sub&gt;A&lt;/sub&gt;</th>
<th>FIM&lt;sub&gt;D&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Stroke</td>
<td>Male</td>
<td>85</td>
<td>Cane</td>
<td>Right</td>
<td>Left</td>
<td>87</td>
<td>113</td>
</tr>
<tr>
<td>P2</td>
<td>Stroke</td>
<td>Male</td>
<td>63</td>
<td>Cane</td>
<td>Right</td>
<td>No paresis</td>
<td>69</td>
<td>107</td>
</tr>
</tbody>
</table>

FIM<sub>A</sub> = admission total FIM, FIM<sub>D</sub> = discharge total FIM.
Data Processing

- Acceleration Signals
- Angular Velocity Signals
- AC Component Times
- Anthropometric Measurements

- Timestamp Alignment
- Orientation Correction
- Gait Cycle Event Detection & Computation Algorithms
- Band Pass Filtering

- Clinical Assessments of Progress
- Whole Body Movement Metrics
- Gait Features

- Reliable Change Index Analysis
- Standardized Mean Difference Effect Size Analysis
Gait Analysis

- **Gait cycle events**
  - Initial contact (IC)
  - Terminal contact (TC)
  - Mid-swing (MS)

- **Support periods**
  - Single (one limb)
  - Double (both limbs)
  - Triple (both limbs + cane)

Greene et al. 2010, Faruqui, 2010
Participant P1’s gait cycles
Gait Cycle Features

• Note: each trial $t$ has $N_t$ gait cycles

For each gait cycle $GC_i$ ($i = 0; i < N_t; i + +$):
  – Compute and store:
    • Cycle duration: $\text{Lead}_{IC_{i+1}} - \text{Lead}_{IC_i}$
    • Stance %
    • Mid-swing °/s
    • Cane stance percent ratio: $\frac{\text{Contralateral}_{Stance_i}}{\text{Cane}_{Stance_i}}$
    • Cane swing temporal offset: $|\text{Cane}_{MS_i} - \text{Contralateral}_{MS_i}|$
    • Double support %
    • Triple support %

• For each feature:
  – Compute mean and coefficient of variation for all $N_t$ gait cycles
# Gait Feature Results

<table>
<thead>
<tr>
<th>Metric</th>
<th>P1 $\mu_{S1}$ ($P1 CV_{S1}$)</th>
<th>P1 $\mu_{S2}$ ($P1 CV_{S2}$)</th>
<th>P1: Fewer GCs</th>
<th>P2 $\mu_{S1}$ ($P2 CV_{S1}$)</th>
<th>P2 $\mu_{S2}$ ($P2 CV_{S2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of cycles per trial</strong></td>
<td>8, 7</td>
<td>8, 7</td>
<td></td>
<td>14,12</td>
<td>9,9</td>
</tr>
<tr>
<td><strong>Cycle duration in milliseconds</strong></td>
<td>1377.79 (4.04%)</td>
<td>1221.33 (5.18%)</td>
<td>Shorter GCs</td>
<td>1398.95 (5.29%)</td>
<td>1308.91 (7.68%)</td>
</tr>
<tr>
<td><strong>Left stance %</strong></td>
<td>57.67% (4.45%)</td>
<td>56.44% (3.73%)</td>
<td></td>
<td>63.08% (7.37%)</td>
<td>59.03% (4.53%)</td>
</tr>
<tr>
<td><strong>Right stance %</strong></td>
<td>58.82% (4.73%)</td>
<td>58.18% (5.34%)</td>
<td></td>
<td>58.82% (5.58%)</td>
<td>59.26% (6.41%)</td>
</tr>
<tr>
<td><strong>Cane stance %</strong></td>
<td>46.91% (6.11%)</td>
<td>43.60% (8.48%)</td>
<td></td>
<td>46.33% (23.04%)</td>
<td>40.26% (13.23%)</td>
</tr>
<tr>
<td><strong>Left mid-swing °/s</strong></td>
<td>282.86 (9.79%)</td>
<td>321.70 (14.71%)</td>
<td>Swings w/higher velocity</td>
<td>249.76 (18.74%)</td>
<td>292.47 (9.93%)</td>
</tr>
<tr>
<td><strong>Right mid-swing °/s</strong></td>
<td>286.91 (6.66%)</td>
<td>320.81 (7.53%)</td>
<td></td>
<td>240.43 (14.76%)</td>
<td>276.11 (12.51%)</td>
</tr>
<tr>
<td><strong>Cane mid-swing °/s</strong></td>
<td>140.88 (7.94%)</td>
<td>153.24 (13.19%)</td>
<td></td>
<td>58.45 (27.88%)</td>
<td>66.61 (26.38%)</td>
</tr>
<tr>
<td><strong>Cane stance ratio</strong></td>
<td>1.24 (7.26%)</td>
<td>1.30 (9.17%)</td>
<td>Lower variability</td>
<td>1.33 (22.88%)</td>
<td>1.49 (13.20%)</td>
</tr>
<tr>
<td><strong>Cane swing offset</strong></td>
<td>112.59 (39.43%)</td>
<td>164.21 (30.92%)</td>
<td></td>
<td>94.20 (103.72%)</td>
<td>110.90 (59.80%)</td>
</tr>
<tr>
<td><strong>Double support %</strong></td>
<td>16.49% (23.89%)</td>
<td>14.62% (29.08%)</td>
<td>Less time in support</td>
<td>21.90% (16.16%)</td>
<td>18.34% (30.07%)</td>
</tr>
<tr>
<td><strong>Triple support %</strong></td>
<td>6.50% (41.04%)</td>
<td>5.72% (74.28%)</td>
<td></td>
<td>7.99% (78.43%)</td>
<td>6.54% (87.39%)</td>
</tr>
</tbody>
</table>

CV = coefficient of variation, P1 = participant 1, P2 = participant 2, S1 = session 1, S2 = session 2, and $\mu$ = mean.
Stance and Swing Phase Plots

- Visualizes the variability of timing between both legs and a cane
- Stance (gray) and swing (blue) phases
- Y-axis groups sensor location
- X-axis shows an estimate of the percentage of the gait cycle
- Overlaid hatch are support periods of:
  - Double (star hatch)
  - Triple (cross hatch)

Participant P1’s S2 stance and swing phase plot
P2 Cane Movement

- More variable gait
- Only one period of triple support each cycle
  - Different behavior at S1 testing

Participant P2 (S2)
Detecting Incorrect Cane Usage

- Incorrect cane use [2]
  - Swinging the cane in phase with the ipsilateral leg (GC #0)
  - Holding the cane in the air for multiple steps
- Missing cane IC within a gait cycle

Participant P2 (S1)
Closing Thoughts

• Limitations
  – Low sample size (N=2)
  – Gait cycle event detection algorithm has not been laboratory validated

• Future work
  – Collecting data from additional participants using different assistive devices
  – Designing a real-time system monitoring system
References


• Images courtesy of:
  – St. Luke’s Rehabilitation Institute, Spokane, WA
  – [http://www.upmc.com/patients-visited/education/PublishingImages/P-S/QuadCane-1.jpg](http://www.upmc.com/patients-visited/education/PublishingImages/P-S/QuadCane-1.jpg)
  – Faraqui, 2010
Thank You

• Questions?
• Contact information
  – Gina Sprint
  – gsprint@eecs.wsu.edu
  – www.eecs.wsu.edu/~gsprint

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