Standing and Locomotion in Paraplegics

- Functional Goal: Home and Workplace Mobility for Individuals Having Paraplegia
- Clinical Rationale:
  - Health and Economic Benefits of Improved Mobility Functions
  - Health and Economic Benefits of Exercise, Social Interaction and Mobility for These Patients
‘Servo’ Control for Standing

- Feedback control of joint position in real time, on the basis of sensor measurements
- Knee angle control
- Ankle angle control
- Hip and trunk abduction and adduction
- Combinations
Approaches

- FES
- External orthotics
  - Exoskeletons (current commercial interest)
  - Exoskeleton suits (current commercial interest)
- “Hybrid” FES+Orthotics
Exoskeletons

- Rewalk 6.0 Soft Exoskeleton suit
- Cyberdine -
  [https://www.cyberdyne.jp/english/](https://www.cyberdyne.jp/english/)
- Photo comparison
  [https://www.therobotreport.com/3-exoskeleton-companies-go-public/](https://www.therobotreport.com/3-exoskeleton-companies-go-public/)
The FES Locomotion Problem
FES Gait

- SCI patients with intact peripheral nerves
- Electrodes implanted near motor point of large muscles
- Internal or external stimulator(s) generate(s) electrical pulses to cause muscle contraction
- External control unit contains the stimulation patterns to produce stepping
- Thumbswitch held by patient controls pattern progression
Paraplegic Walking With FES
FES System Components

- **Electrodes**
  - Epimysial
  - Intramuscular
  - Nerve cuff

- **Stimulators**
  - External or implanted

- **Types of Stimulation**
  - Modulation of pulse width
  - Modulation of stimulus period (interpulse interval)
FES System Components

- **External Control Units**
  - computer and software
  - power supply
  - mounting
  - command source (finger-mounted thumb switch)
FES System Components

- **Supporting Devices**
  - walker (four post or rolling)
  - straight arm canes or crutches
  - Passive orthoses (AFO, KAFO, HKAFO)
  - assistants
Pre-Programmed Stimulation for Locomotion Tasks

- **Patient Triggered**
  - Patient initiates each successive portion of the gait cycle, using hand switch

- **Switch Triggered**
  - Successive portions of gait cycle also triggered from sensor information
  - e.g., Foot switches, force sensitive resistive insoles
Gait Cycle

- Heel Strike
- Weight Acceptance
- Foot Flat
- Mid Stance
- Heel Off
- Toe Off
- Max Knee Flexion
- Early Swing
- Late Swing
- Terminal Stance
FES vs Normal Gait

- Foot flat posture of FES gait
- Normal double stance posture
- Foot flat and straight knee postures produce large center of mass displacement in FES gait
- Compensatory measure for loss of momentum in FES gait produces a high kick at the end of swing

- Specification of precise muscle activation and timing is difficult
Performance of First Generation Systems

- **32-48 channels**
  - distances: 300m average, 1.5 km max
  - speeds: 1 m/s max over first 100 m, 0.7 m/s average
  - slopes, stair climbing and descent with walker or one crutch/one rail
  - percutaneous electrodes –*a problem*
Performance of First Generation Systems

- 16 channel walking
  - shorter distances
  - slower (0.4 m/s average)
  - minimal stairs
  - can be made fully implantable (two 8 channel implants)
Achievements & Limitations

- Limitations of a “fixed” stimulation pattern:
  - Variability of muscle sensitivity
    - Step-to-step, day-to-day gait variability
    - Fatigue, muscle conditioning
  - No compensation for external disturbances
  - Trial & error stimulation pattern adjustments based upon visual observation of gait
Fatigue of Electrically Stimulated Muscle

- A major problem for extended duration locomotion
- Loss of muscle response can degrade performance (and possibly compromise safety)
- Difficult to detect early
  - No force or torque sensor
  - Variability of response
Evoked EMG signals can be used to recognize and characterize the onset of fatigue

Done by tracking changes in pole locations of linearized models of excitation subsystem (stimulation-to-EEMG) and activation subsystem (EEMG-to-torque) during stance phase
Control Issues

- Time delay between stimulation and muscle force production: 100-300 msec
- In dynamic walking, time spent in some phases: 100 msec
- By the time the effect of the stimulation can be observed, the stimulation for the next phase is proceeding.
‘Servo’ Controllers Can’t Work for Fast FES Locomotion

The elapsed time spent in certain phases of paraplegic FES gait is approximately the same as the response time of stimulated muscle---

by the time a sensor-driven feedback control correction is made, the walking has moved to the next phase of gait
Approaches to Solving this Problem

- **‘Open Loop Feedback’ Perturbation Control**
  - Use sensor information to modify future feedforward control

- **Time (Cycle) Shifting**
  - Use error measurements to drive feedback controller, but apply it to the next gait cycle

- **Learning Control**
  - ‘Learn’ problems and adjust pre-programmed stimulation (ALN’s, fuzzy logic, ANN’s)
‘Next Step’ Correction of FES-Generated Locomotion

- Use sensor and stimulator information to modify the stimulation pattern of the next step of the gait cycle (or later phases of the same one)

- Three aspects:
  - Gait Event Detection
  - Gait Evaluation
  - Gait Correction
Control System

Cycle-to-Cycle Control

Command Input

Stimulator

Paraplegic Subject

FES Gait

Sensor Information

Gait Event Detection Module

Gait Cycle Information

Pattern Adjustment Module

Gait Evaluation Module

FES Gait Controller
Gait Event Correction

- *Given the detected phase of gait (of each leg) at each time, the on-board computer can use sensor information to evaluate the quality of the locomotion*

- *After each gait cycle, gait anomalies are then recognized*

- *Then hand-crafted correction rules are used to modify the stimulation pattern to correct these problems*
Obtaining Gait Event Detector

- Collect data from walking trials of subject
  - sensor data
  - stimulator status data
  - video recordings of locomotion
- Extract gait phase detection rules
  - from data and from gait phases determined (by experimenter) from video
  - fuzzy logic systems identification methods
Hierarchical structure for gait event detection

- Fuzzy System Identifier makes initial determination of when phases of gait occur, based upon sensor signals
  - Rules identified from sampled sensor and stimulator data as well as human expert-determined estimates of the phase of gait (from video recordings)
- Supervisory rules then used to enforce “common sense” constraints
The supervisory rules detect the gait events labelled with arrows while ignoring the incorrect phases of gait estimated during *mid stance* and *early swing*. [Skelly and Chizeck, IEEE Trans. Neural Systems and Rehab, March 2001]