Robotic Assistive Devices to Improve Quality of Life for Persons with Amputation and Paraplegia

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Objectives

• Present and discuss the status of emerging robotic leg prostheses intended to enable enhanced locomotion for lower limb amputees.

• Present and discuss the status of emerging robotic multigrasp hand prostheses intended to enable enhanced dexterity for upper extremity amputees.

• Present and discuss the status of emerging lower limb robotic exoskeleton technology intended to provide legged mobility to persons with paraplegia.
Emergence of Powered Prostheses

- Typical above-knee prosthesis consists of a damper at the knee joint and relatively stiff leaf spring for the ankle/foot complex.

- These prostheses are energetically passive devices (i.e., they cannot contribute net power to gait).

- These prostheses provide a relatively small subset of the functionality of the intact limb.

- Recent advances in robotics technology enable a fully powered leg capable of biomechanical levels of torque and power within the size and weight constraints of a lower limb prosthesis.

- Such devices offer the potential to provide a much greater level of functionality to the amputee.
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Vanderbilt Powered Prosthesis

- Currently the only integrated powered knee and ankle transfemoral prosthesis.
- Actuation: Two 200W rare-Earth-magnet brushless DC motors with ~190:1 transmissions.
- Power: Lithium polymer battery.
- Sensors: Prosthesis configuration and shank load.
- Intelligence: Two on-board microcontrollers.
- Total mass of prototype as shown: 4.2 kg* (9.3 lb).

*Corresponds to intact limb mass of 105 lb person.

Generation One Vanderbilt Prosthesis
Control of a Powered Prosthesis

- Power requires a paradigm shift in the interface between user and prosthesis
  - Passive prostheses cannot move without power from the user (movement is fundamentally under direct user control).
  - A powered prosthesis can move autonomously.
  - A microcontroller must sit at the interface between the user and prosthesis to enable the user to control movement (i.e., controller must use sensing to infer and execute intended functionality).

- We have developed a controller that:
  - Uses sensors exclusively contained within the prosthesis
  - Implicit (infers intent based on user’s natural movements)
  - Provides biomechanically appropriate behavior
  - Synergistically coordinates the movements of the knee and ankle
  - Defaults to passive behavior
Level Walking

Walking Cadence Evaluation
Slow, Self-Select, Fast

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Comparison with Healthy Biomechanics
Biomechanical Function of Push-off

- **Passive prosthesis**
  - Little if any forward propulsion provided by prosthesis.
  - Hip on the prosthesis side sources all power for swing phase.
  - Often results in underpowered swing phase with little toe clearance.
  - Increases likelihood of scuffing and/or stumbling.
  - Often results in heel hiking, particularly up slopes, uneven terrain.

- **Prosthesis with powered push-off**
  - *Powered push-off from prosthesis propels amputee forward.*
    - Reduces metabolic energy consumption.
  - *Powered push-off drives swing leg forward.*
    - Enhances swing knee flexion and toe clearance.
    - Decreases likelihood of scuffing or stumbling.
    - Eliminates tendency for heel hiking.
  - Swing phase load on hip is dramatically decreased.
Biomechanical Benefits of Power

- **Self-selected speed** of level walking:
  - Passive prosthesis: 4.1 km/hr @ 90 steps/min
  - Powered prosthesis: 5.1 km/hr @ 90 steps/min
  - **Subjects walk 24% faster with powered prosthesis**

- **Metabolic energy consumption**:
  - Measurements taken on treadmill @ self-selected speed for passive prosthesis (3.2 km/hr)
  - Oxygen uptake was **23.2% greater with passive prosthesis**
  - If metabolic baseline is subtracted, oxygen uptake was **38.7% greater with passive prosthesis**
Other Terrain Types

- Previous results for level walking.
- People typically traverse a variety of terrain types (up/down slopes, up/down stairs).
- Passive prostheses are particularly limited in their ability to provide appropriate biomechanics across varying terrain types.
- Powered prostheses can emulate the behavior of the healthy limb, and therefore are much better able to provide healthy biomechanics across terrain types.
Biomechanics of Upslope Walking

![Graph showing knee and ankle joint angles for different walking conditions.](image-url)
## Benefits in Upslope Walking

<table>
<thead>
<tr>
<th></th>
<th>Push-Off</th>
<th>Swing</th>
<th>Heel Strike</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Powered</strong></td>
<td><img src="#" alt="Image" /></td>
<td><img src="#" alt="Image" /></td>
<td><img src="#" alt="Image" /></td>
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<tr>
<td><strong>Passive</strong></td>
<td><img src="#" alt="Image" /></td>
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</tbody>
</table>
Slope Walking

Passive Prosthesis

10 Degree Slope
Falls in Lower Limb Amputees

• The annual incidence of falls in the lower limb amputee population exceeds that of the elderly population.

• The rate of seeking medical attention as a result of such falling is comparable to that of the institution-living elderly.

• The incidence of falling (and requiring medical attention due to such falls) is higher in younger than in older amputees.

• In a survey of 435 lower limb amputees, Miller et al. (2001) conclude that “falling and fear of falling are pervasive among amputees.”

• In a survey of 396 lower limb amputees, Gauthier-Gagnon et al. (1999) report that 50% of respondents reported that they had to “think about every step they made.”
Decreasing Incidence of Falls with Power

• During **standing**:
  
  • Real-time ground slope adaptation enables powered knee/ankle prosthesis to provide full balance support in varying ground conditions.

• During **walking**:
  
  • Powered push-off, powered swing phase, intelligent stance phase decreases likelihood of scuffing, stumbling, and falling.
  
  • Slope and stair appropriate biomechanics decreases likelihood of scuffing, stumbling, and falling.
  
  • Active stumble recovery behaviors (under investigation) can potentially decrease the likelihood that a stumble (or scuffing) results in a fall.
Ground Slope Adaptation

Passive Prosthesis Weight Bearing Ratios

-15 -10 -5 0 +5 +10 +15

Load (N)

Powered Prosthesis Weight Bearing Ratios

-15 -10 -5 0 +5 +10 +15

Ground Slope
Providing Active Recovery Responses

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Powered Prosthesis

Preliminary Stumble Reactions

Center for Intelligent Mechatronics
Generation 2 Prototype
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Generation 2: Walking/Standing
Generation 2: Stairs
Generation 2: Running
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Commercial Hand Prostheses

- **Body-powered prosthesis**
- **Myoelectric prosthesis**

- Shoulder harness pulls cable to open hook
- Both are single degree-of-freedom devices (open/close only)
  - Electrodes on skin surface measure muscle contraction in residual limb and open/close "hand" via electric motor
Vanderbilt Multi-Grasp Hand

Generation Three VMG Hand
VMG Hand Postures/Grasps

- Platform
- Point
- Hook
- Lateral Pinch
- Tip
- Tripod
- Spherical
- Cylindrical
VMG Hand Design

Digit I: Opposition/Reposition
Digit II: Flexion/Extension
Digit I: Flexion/Extension
Digit III-V: Flexion/Extension
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Vanderbilt Multi-Grasp Hand

Fingertip Force

Finger Motion Bandwidth

<table>
<thead>
<tr>
<th>Target Values*</th>
<th>Achieved Values</th>
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</thead>
<tbody>
<tr>
<td>Digit I F/E</td>
<td>25 N</td>
</tr>
<tr>
<td>Digit II F/E</td>
<td>25 N</td>
</tr>
<tr>
<td>Digits III-IV F/E</td>
<td>14 N</td>
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<tr>
<td>Hand Bandwidth</td>
<td>1.5 Hz</td>
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<tr>
<td></td>
<td>3.5 – 6 Hz</td>
</tr>
</tbody>
</table>

*See publication for details
Control of a Multigrasp Hand Prosthesis

- Trade-off exists between functionality and cognitive effort.
- Single DOF myoelectric hand provides intuitive, real-time, robust, reliable, proportional control.
- User must be able to access multifunctional capability of hand in a natural and efficient manner.
- Multigrasp control interface should provide intuitive, real-time, robust, reliable, proportional control.
Multigrasp Myoelectric Control

Symbol Key:
- A1 = DII Flex/Ex Actuator
- A2 = DIII-V Flex/Ex Actuator
- A3 = DI Flex/Ex Actuator
- A4 = DI Opp/Rep Actuator
- S = State
- D = Displacement
- F = Force
- Th = Threshold

A1: Rest position
A2: Opposite position
A3: Hook
A4: Point
S1: Reposition
S2: Point
S3: Hook
S4: Lateral Pinch
S5: Opposition
S6: Tip
S7: Cyl/Sph/Tri

Property of Vanderbilt University and the Shepherd Center
Vanderbilt MMC Demonstration

Multigrasp Myoelectric Control of Vanderbilt Multigrasp Hand Prosthesis
Functional Assessment

Functional Assessment of a Multigrasp Myoelectric Prosthesis: An Amputee Case Study
## Preliminary Assessment Results

<table>
<thead>
<tr>
<th>Functionality Profile</th>
<th>VMG &amp; MMC</th>
<th>DMC*</th>
<th>i-LIMB*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole Hand</td>
<td></td>
<td></td>
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<tr>
<td>Extension</td>
<td>89</td>
<td>81</td>
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<td>Spherical</td>
<td>87</td>
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<td>Power</td>
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<td>Precision</td>
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<tr>
<td>Lateral</td>
<td>88</td>
<td>69</td>
<td>23</td>
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<tr>
<td>Tripod</td>
<td>71</td>
<td>76</td>
<td>32</td>
</tr>
<tr>
<td>Tip</td>
<td>59</td>
<td>39</td>
<td>42</td>
</tr>
<tr>
<td>Index of Function</td>
<td>81</td>
<td>74</td>
<td>52</td>
</tr>
</tbody>
</table>

Lower Extremity Exoskeletons for SCI

- Recent advances in robotics technology enable powered lower limb exoskeletons that can assist with legged mobility for persons with paraplegia.
- Several such systems currently emerging
- These systems will not replace a wheelchair as primary means of mobility.
- Such systems can provide:
  - Enhanced accessibility and freedom (i.e., access to and mobility within places that are not easily accessible by wheelchair).
  - Social and psychological benefits associated with enhanced freedom.
  - Physiological benefits associated with weight bearing movement.
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Some Emerging Devices

- **ReWalk**
  - Weight: 45-50 lb
  - Control: Wrist pad and torso tilt
  - Only FDA-approved exo

- **Ekso**
  - Weight: 45-50 lb
  - Control: Therapist keypad or arm sensors

- **Rex**
  - Weight: 85 lb
  - Control: Joystick
  - Only exo that does not require stability aid

- **Parker**
  - Weight: 27 lb
  - Control: Hands-free, based on posture
Parker Exoskeleton

- Jointly developed under NIH funding by Vanderbilt University and the Shepherd Center.
- Licensed by Parker Hannifin for commercial translation in 2012.
- Expanded clinical trials starting mid-2013.
- Anticipated commercial release in 2014.
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Fully Integrated Robotic Components

Battery
Master
Slave
Some Unique Features

- Total weight is 12 kg (27 lbs)
- Used with standard AFOs
- Exoskeleton does not extend under feet or over shoulders
- Compact frontal profile and absence of backpack enables sitting in wheelchair, armchair, car seat, etc.
- Snaps together and apart to facilitate self-donning/doffing, transport, storage, and handling
- Legged Segway control approach enables hands-free control of movement
- FES option provides exoskeleton-controlled supplemental use of FES (currently quads and hamstrings)
Posture-Based Autonomous Control
Posture-Based Control Demonstration
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Stand/Walk/Sit Demonstration
Stairs Demonstration
Several exoskeletons are emerging, but little has been reported regarding benefit, and methods and metrics for assessment are not yet standardized.

Recent study of ReWalk by Esquenazi et al (Nov 2012)
- 11 subjects, T3-T12 complete
- 10MWT and 6MWT for mobility
  - 10MWT: average 89 s, stdev 114 s
  - 6MWT: average 77.5 m, stdev 45 m
- Change in HR as exertion measure, but protocol unclear
- 3/11 subjects reported improved spasticity, 0/11 reported pain resulting from exo, 1/11 reported fatigue from exo, 5/11 reported improved bowel regulation.
Assessing Mobility Benefit

- Recent case study of Parker/VU/Shepherd exoskeleton by Farris et al (in press):
  - T10 complete subject
  - Compares mobility and exertion with exo versus braces
  - 10MWT, 6MWT, and TUG for mobility
  - Change in HR as exertion measure

![6MWT Distance](image1)

![TUG and 10MWT Times](image2)
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Exertion and Efficiency

Conclusion of Case Study

Legged mobility with the exoskeleton (relative to braces) provides:

- Significant improvement in walking speed (40% increase with exo)
- Significant decrease in exertion (45% decrease with exo)
- Significant increase in efficiency of movement (between 2 and 5 times greater, depending on assessment instrument).
Supplemental FES

• FES has been documented to provide important physiological benefits, such as:
  • reducing incidence of decubitus ulcers
  • improving cardiovascular health
  • aiding bowel and bladder function
  • reducing muscular spasticity
  • retarding osteoporosis

• FES-aided gait systems have thus far provided limited functionality due to:
  • Rapid muscle fatigue and potential consequences of such fatigue
  • Lack of robust control of limb movement from stimulated muscle

• These limitation are all eliminated with exoskeleton:
  • Exoskeleton controller solicits maximum contribution from stimulated muscle
    and “fills in” the rest with motor torque
  • No consequences of muscle fatigue, since exo provides backup
  • Muscle used for power, but control provided by exo, so movement is robust
    and consistent
Plug-In Multichannel E-Stim Module

Stimulator Board
Main Board
• Hamstring stimulation used for hip extension during stance phase of walking.
• Quadriceps stimulation used for knee extension during swing phase of walking.
• Stimulation timing and levels automatically adjusted (on step-by-step basis) by the exoskeleton controller to provide as much assistive joint torque as possible.
• Joint motion and torque measured by exoskeleton during exoskeleton walking with and without FES.
• Data on following slides summarize 120 steps with FES and 120 steps without.
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Movement with and without FES

Hip and knee movement highly repeatable regarding supplemental FES

Stance phase hip angle

Swing phase knee angle
Stimulated hamstrings provide 27% of hip torque during stance

Stimulated quadriceps provide 44% of extensive knee torque during swing
Supplemental FES Conclusions

• Exoskeleton provide effective control of FES
• Control is self-adjusting and transparent to the user.
• Cooperative control ensures reliable, robust, consistent motion, regardless of fatigue or muscle controllability challenges.
• FES provides physiological benefits to patient
• FES contributes significant torque to movement
  • Provides exercise to patient
  • Increases battery life of exoskeleton
Walking Outside