Artificial Muscle Actuators for Upper Limb Prostheses

Presented by:
Faranak Farzan and Pawel Pietruszczak
The Amputee Population

- National Center for Health Statistics estimates for the USA:
- Major amputations occur in 1 out of 300 individuals: 23% of this population represents upper limb amputees
- A continual need for prosthetics, with over 50,000 amputations every year
- Demographics estimate: 60% of amputees are between 21-64 years, 10% under 21 years of age

- Primary Causes of upper extremity amputation:
  - Trauma: 77%
  - Congenital: 8.9%
  - Tumor: 8.2%
  - Disease: 5.8%
The Clinical Solution:
Upper Extremity Prostheses

- Prosthetics have been around for thousands of years, with early prosthetics made out of leather, wood and metal.

- Development of prosthetics in the past century largely a result of wars.
- US Civil War (1861-1865) Government provided prostheses for veterans.
- 1863 – invention of rubber: cosmetic dimension to prostheses.
- First functional moving hand produced in Russia (1960).
- First commercially available electrical prostheses in the US available since 1980s.

- Currently available prosthetics include passive, body powered, and electrical prostheses with silicone covers or hooks.

- Evolution has been towards more extensive control, function and cosmetics.
The Prosthesis Clinical Reality

- Of a population of 10,000 new upper limb amputees per year, only half are fitted with a prosthesis.
- Half of those fitted with prosthesis continue to use their replacement limb at the end of a year.
- 30-50% of patients do not use their prosthetic hand regularly.

- Engineering solution must maintain a focus on patient choice to find an optimal solution:
  - Personal choices: Patient motivation, appearance, performance requirements.
  - Work within Patient Limiting Factors: length and degree of amputation, weight tolerance, muscle strength, skin condition, stress from activities.
Current Solutions

- **Passive Prostheses**
  - Focus on cosmetic issues
  - Cosmetic engineering focus: (stain resistance, natural appearance, durability)
  - Available for prostheses ranging from single digits, to full limbs and covers for existing prostheses

- **Advantages**
  - Not drawing attention to the prostheses user

- **Disadvantages**
  - Low degree of manipulative functionality
  - Addition to a powered prosthesis lowers mechanical functionality

http://www.alatheia.com/
Current Solutions

- **Body-Powered Prostheses**
  1. Gross body movements - captured by a harness attached to a cable system that connects to a terminal device (ie hook, hand)
     - Patient must have sufficient residual limb length, musculature and range of motion
     - Minimum ability of one shoulder movement or chest expansion
  2. Finer muscle movements
     - Requires surgical procedure of Cineplasty
     - Prior to prosthesis, loops of muscle are surgically isolated and amplified for movement output

- **Advantages:**
  - Lightweight
  - Increased control due to proprioception (feedback from harness system/muscles)
  - Low cost - makes prosthesis accessible

- **Disadvantages:**
  - Harness system: may be uncomfortable. Control is restrictive
  - Functional envelope limited from waist to mouth
  - Control movements draw attention to users
Current Solutions

- **Externally Powered Prostheses**
  - example: UTAH arm (electrically powered)
  - Microprocessor controlled
  - Uses electrical signals from surface electrodes generated by muscle contraction
  - Input control either determined by the magnitude or location of muscle contraction

- **Advantages:**
  - Cosmetically pleasing
  - Sensitive control of elbow, hand and wrist

- **Disadvantages**
  - Learning Curve
  - High cost, maintenance
  - Less user feedback
  - Lacks many degrees of freedom
Modeling an Advanced Prosthetic Hand

- **Environment Module**
  - Rain, External Forces, Temperature Fluctuation,

- **Assembly Module**
  - Mechanical Housing and Structural Element

- **Measurement Module**
  - Force, Pressure, Temperature

- **Communication Module**
  - Transmits information between the modules within the system (e.g., wires)
Modeling and Advanced Prosthetic Hand

- **Actuation Module**
  Drives that cause the motion of the hand and produce the force needed to carry out activities. (Artificial Muscles)

- **Interface Module**
  The Link between the user and the interface.
  eg. Myoelectric sensors, Neural Interface

- **Processor Module**
  Responsible for processing storing and utilizing the information provided by the interface module and the measurement module.

- **Software Module**
  Operating instructions
  Defines the algorithm for the processing module
Bradley Diagram

Electric Signal

- Interface module
- Processor module
- Communications module
- Actuation module
- Assembly module
- Measurement module
- Environment module
- Software module
Current Developments: Biomechanical Challenge

- Human hand has 15 joints (including the wrist)
- 40 muscles controlling the hand, including intrinsic and extrinsic
- Current goal in a upper limb prosthesis: to mimic all the motor functions of the human hand
- Provide dexterity: allow a full range of motion, with sufficient force and control
Biomechanical Challenge

- Total 21 DOF in the human hand
  - (not including wrist)
- Interphalangeal joints: 1 Degree of Freedom (DOF)
  - Flexion/extension
- Metacarpophalangeal joints: 2 DOF
  - flexion/extension & abduction/adduction
- Thumb joint has additional 2 DOF
- Wrist has 6 DOF
Current Developments: Actuators

To meet the constructive and functional needs, actuators need to aim for:

- Lightweight
- Small size
- Low energy consumption
- High Torque
- Quiet Operation
- Minimum heat generation
- Fast response
- Easy control
Actuators

- **Conventional Actuators**
  - Operating principle is based DC motors
  - E.g. DC Micromotors, Servomotors, Hydraulic and Pneumatic actuators

- **Non-conventional Actuators (potential)**
  - Operating principle is based on material’s atomic structure
  - E.g. Metal alloys, Piezoelectric materials, Polymeric gel type materials, Electro Active Polymers
Conventional Actuators

I) DC motors
Coreless/Brushless DC Micromotors

8mm-48mm, 0.18-15 Watt
Long operational life, Reliable
Response to control is sensitive, fast & precise
High rotation → Loud distracting noise
Low torque → Weak strength, slow motion &
gearboxes required to set them in motion
Brush-switch set → Requires maintenance

Brushless Micromotors
More compact → Easily fitted into the
Prosthetic cavity
No brush → No maintenance
Conventional Actuators

II) Servomotors
Consists of DC micromotor reduction system control system
- High Torque
- Low cost

Sao Carlos Finger: (prototype phase)
- Inexpensive
- Light and compact
- 3 DoF per finger (3 phalanges)
Hydraulic and Pneumatic Actuators

- **Pneumatic Actuator**: Ie McKibben Artificial Muscle
  - **Advantages**:
    - Similar force-length properties of human muscle, but not force-velocity properties
    - Studied extensively, many models developed
  - **Disadvantages**:
    - Difficulty in minimizing size of tubes (force proportional to square of tube’s radius) – low DOF
    - Low operating frequency
    - Loud operation

- **Hydraulic Actuator**:
  - Uses a DC micrometer to generate mechanical energy transferred to a fluid
  - Motor can generate 0.6 MPa of hydraulic pressure
  - **Advantages**:
    - High power efficiency
    - Amplifiable force output
  - **Disadvantages**:
    - Low flexibility – low DOF
    - Low operating frequency
Unconventional Actuators: Polymers

- Undergo a reasonable amount of strain when exposed to external stimulus such as: chemical, thermal, electrical

- Abrupt changes in volume, Low mass, Occupy little space, Simulate movements of natural muscles (e.g. Frequency, efficiency, Max $\sigma$, Energy/Area, Power/Volume), Generate High Forces

Differ in Composition (gels, solids, liquids) and type of stimulus

- PAA $\rightarrow$ Polyacid acrylic $\rightarrow$ change in PH.
- NIPA $\rightarrow$ N-isopropylacrylamide $\rightarrow$ thermally stimulated
- PAM $\rightarrow$ Polyacrylamide $\rightarrow$ Electric Field

- EAPS: ELECTRO ACTIVE POLYMERS
  Plastic that change shape in response to ELECTRICITY.

  Ionic EAPs          Electronic EAPs
Ionic EAPs

- Work on the bases of electrochemistry
  “Mobility and diffusion of changed ion”

Pros:
- Low voltage (single digit!)
  Can run directly off batteries (Portable)

Cons:
- Need to be wet (coating)
- As long as electricity is on, muscle keeps moving (permanent damage)
Electronic EAPs

E.g. elastomers, acrylic elastomers, electrostrictive elastomers.

- Driven by electric field

**Pros & Cons:**

- React quickly
  - deliver strong mechanical forces
- No protective coating
- Low current but High voltage (2-5 KV)

cause uncomfortable shock
Power delivery is a problem

- Life Cycle (more study)
e.g. Dielectric elastomers
  - 5-10% strain 10 million cycle
  - 50% area strain 1 million cycle
Piezoelectric Actuators

- Based on Piezoelectric materials that convert mechanical displacements (strains) into electrical energy
- An electrical field is applied to the material creating minute strains that are translated into mechanical energy
- Rotary and Ultrasonic Motors

**Advantages:**
- High power density
- Small size, low mass, high torque
- Silent function
- Fast response
- No magnetic fields generated

**Disadvantages:**
- Difficult to build, costly
- Need high frequency energy sources
- Short service life
- Low efficiency (compared with electric)
Shape Memory Alloys

- Ex. Ni-Ti wires
- Exhibit the “Shape Memory Effect” : when heated above a certain temperature, the material returns to a predetermined shape and size
- Heating accomplished through flow of electrical current in material

![Material Crystalline Arrangement During the Shape Memory Effect](image)

*Figure 1. Material Crystalline Arrangement During the Shape Memory Effect*
Shape Memory Alloys

- Has been demonstrated in micro robotic and medical applications
- Successful prototype of a finger with 4 DOF (Rutgers Hand (NJ)). Design of 20 DOF hand.

**Advantages**
- light weight (good strength)
- small size and volume of material, potential for high DOF
- low material cost
- quiet operation
- high force density (high grasping strength)

**Disadvantages:**
- temperature hysteresis - strain/temperature relationship is affected. Control/modeling difficulty
- Problems in consecutive flexion/extension without adjustment (Rutgers)
- Low energy efficiency (improved actuators provide 53.4N at 14.5W -> 6.67N fingertip)
- Low strain (2%-8%)
- Limited life cycle

*Figure 7. Aluminum Finger Prototype*
<table>
<thead>
<tr>
<th>Actuator Type (specific example)</th>
<th>Maximum Strain (%)</th>
<th>Maximum Pressure (MPa)</th>
<th>Specific Elastic Energy Density (J/m²)</th>
<th>Elastic Energy Density (J/cm³)</th>
<th>Coupling Efficiency k² (%)</th>
<th>Maximum Efficiency (%)</th>
<th>Specific Density</th>
<th>Relative Speed (full cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electroactive Polymer Artificial Muscle</td>
<td>215</td>
<td>7.2</td>
<td>3.4</td>
<td>3.4</td>
<td>~60</td>
<td>60–80</td>
<td>1</td>
<td>Medium</td>
</tr>
<tr>
<td>Acrylic</td>
<td>63</td>
<td>3.0</td>
<td>0.75</td>
<td>0.75</td>
<td>63</td>
<td>90</td>
<td>1</td>
<td>Fast</td>
</tr>
<tr>
<td>Electrostrictor Polymer (P(VDF-TrFE))²</td>
<td>4</td>
<td>15</td>
<td>0.17</td>
<td>0.3</td>
<td>5.5</td>
<td>-</td>
<td>1.8</td>
<td>Fast</td>
</tr>
<tr>
<td>Electrostatic Devices (Integrated Force Array)³</td>
<td>50</td>
<td>0.03</td>
<td>0.0015</td>
<td>0.0015</td>
<td>~50</td>
<td>&gt; 90</td>
<td>1</td>
<td>Fast</td>
</tr>
<tr>
<td>Electromagnetic (Voice Coil)⁴</td>
<td>50</td>
<td>0.10</td>
<td>0.003</td>
<td>0.025</td>
<td>n/a</td>
<td>&gt; 90</td>
<td>8</td>
<td>Fast</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceramic (PZT)⁵</td>
<td>0.2</td>
<td>110</td>
<td>0.013</td>
<td>0.10</td>
<td>52</td>
<td>&gt; 90</td>
<td>7.7</td>
<td>Fast</td>
</tr>
<tr>
<td>Single Crystal (PZN-PT)⁶</td>
<td>1.7</td>
<td>131</td>
<td>0.13</td>
<td>1.0</td>
<td>81</td>
<td>&gt; 90</td>
<td>7.7</td>
<td>Fast</td>
</tr>
<tr>
<td>Polymer(PVDF)⁷</td>
<td>0.1</td>
<td>4.8</td>
<td>0.0013</td>
<td>0.0024</td>
<td>7</td>
<td>n/a</td>
<td>1.8</td>
<td>Fast</td>
</tr>
<tr>
<td>Shape Memory Alloy (TiNi)⁸</td>
<td>&gt; 5</td>
<td>&gt; 200</td>
<td>&gt; 15</td>
<td>&gt; 100</td>
<td>5</td>
<td>&lt; 10</td>
<td>6.5</td>
<td>Slow</td>
</tr>
<tr>
<td>Shape Memory Polymer⁹</td>
<td>100</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>–</td>
<td>&lt; 10</td>
<td>1</td>
<td>Slow</td>
</tr>
<tr>
<td>Thermal (Expansion)¹⁰</td>
<td>1</td>
<td>78</td>
<td>0.15</td>
<td>0.4</td>
<td>–</td>
<td>&lt; 10</td>
<td>2.7</td>
<td>Slow</td>
</tr>
<tr>
<td>Electrochemo-mechanical Conducting Polymer (Polyaniline)¹¹</td>
<td>10</td>
<td>450</td>
<td>23</td>
<td>23</td>
<td>&lt; 1</td>
<td>&lt; 1%</td>
<td>~1</td>
<td>Slow</td>
</tr>
<tr>
<td>Mechano-chemical Polymer/Gels (polyelectrolyte)¹²</td>
<td>&gt; 40</td>
<td>0.3</td>
<td>0.06</td>
<td>0.06</td>
<td>–</td>
<td>30</td>
<td>~1</td>
<td>Slow</td>
</tr>
<tr>
<td>Magnetostrictive (Terfenol-D, Etrema Products)¹³</td>
<td>0.2</td>
<td>70</td>
<td>0.0027</td>
<td>0.025</td>
<td>–</td>
<td>60</td>
<td>9</td>
<td>Fast</td>
</tr>
<tr>
<td>Natural Muscle (Human Skeletal)¹⁴</td>
<td>&gt; 40</td>
<td>0.35</td>
<td>0.07</td>
<td>0.07</td>
<td>n/a</td>
<td>&gt; 35</td>
<td>1</td>
<td>Medium</td>
</tr>
</tbody>
</table>
Future

Development of Control system

- increased myoelectric signal processing
- increased user feedback
- direct control using input from the brain

Development of Actuators

- use of the new materials in novel biomechanical configurations
Questions?
References

- Parnianpour et. Al. “Exoskeletal Assistive Devices” http://sina.sharif.edu/~biomech/