

## **Current and Future Uses of Additive Manufacturing in Neurologic, Musculoskeletal, Spinal, and Oncologic Surgery**

---

**Michael J. Yaszemski, M.D., Ph.D.**

**John & Posy Krehbiel Endowed Professor of Orthopedic Surgery and Biomedical Engineering**

**Jane Matsumoto, M.D.**

**Professor of Radiology  
Mayo Clinic, Rochester, MN**

**National Science Foundation**

**Arlington, VA  
March 17, 2016**



## **Disclosure-Yaszemski**

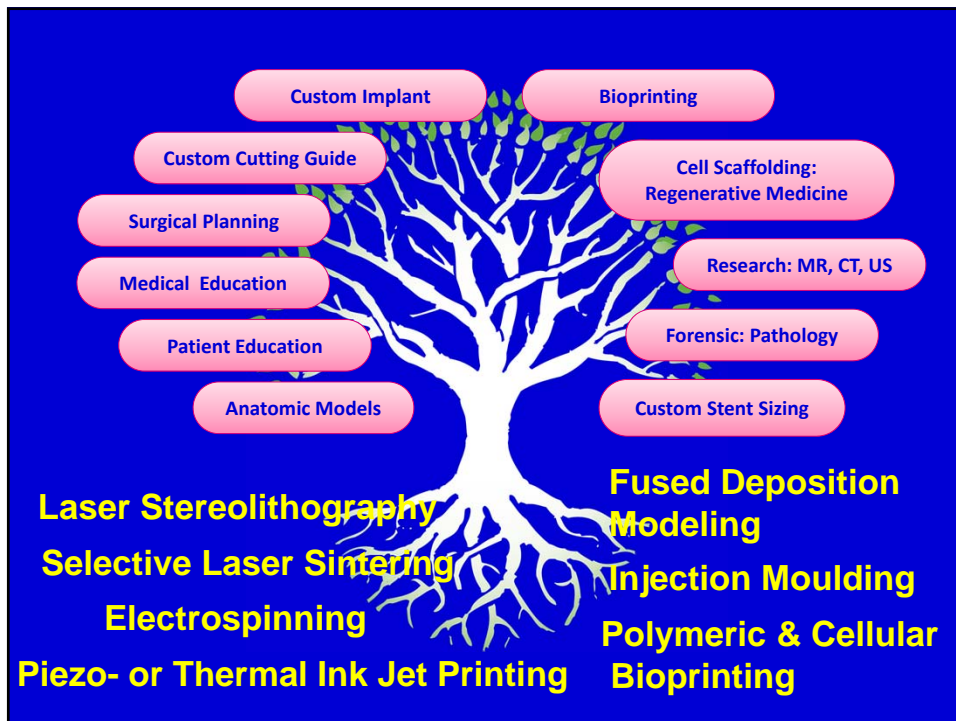
---

- **Mayo Clinic and Dr. Yaszemski hold patents for various biodegradable polymers for use in musculoskeletal system repair.**
- **Grant support from NIH, DOD, Mayo Foundation, and the Krehbiel Professorship**
- **Associate Editor, Journal of Biomedical Materials Research-Part A**
- **Associate Editor, Techniques in Orthopaedics**
- **Consultant, Medtronic, Inc. & K2M, Inc.**



# Disclosure-Matsumoto

- Institutional: Mayo Clinic holds patents for various biodegradable polymers for use in musculoskeletal system repair.



# Outline

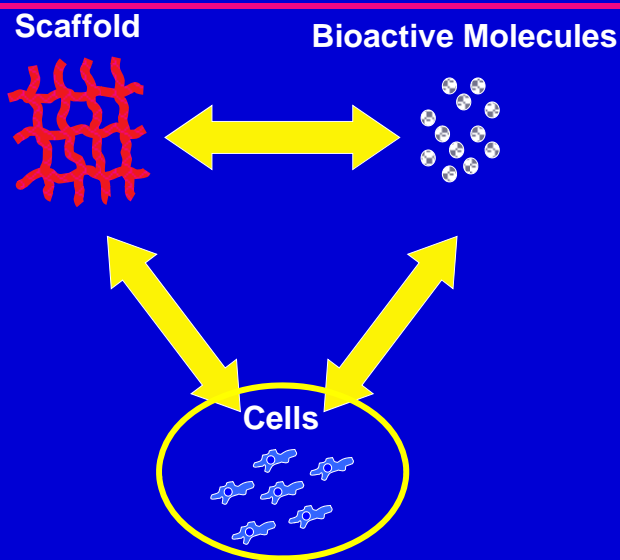
---

- Current uses of additive manufacturing in medicine and surgery
- Illustrative examples
- Gaps in clinical care that might be addressed by additive technologies
- Research needs
- Future vision



# Tissue Engineering Strategy

---

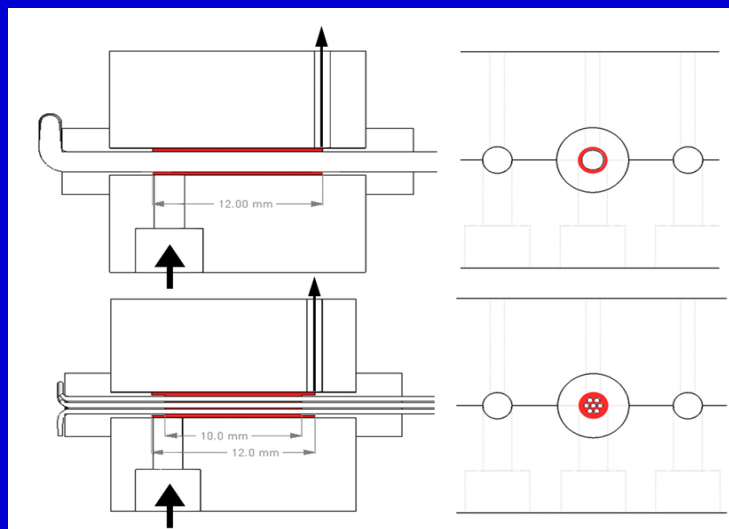


# Scaffolds

- **Polymers**
  - Natural: Silk, chitosan, alginate, collagen, decellularized allograft
  - Synthetic: Polyesters, polyphosphazines, polyanhydrides, polyurethanes
- **Metals**
- **Ceramics**



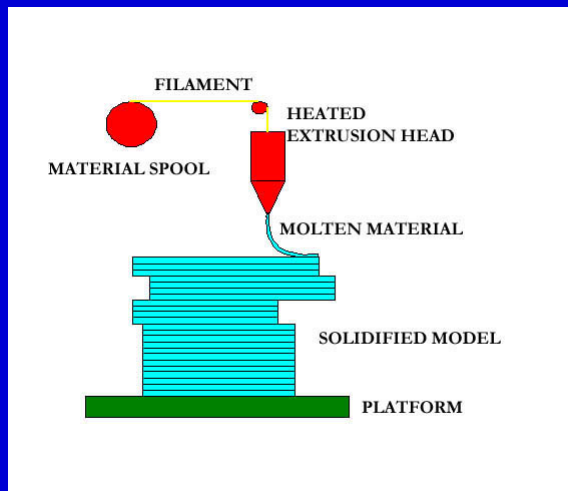
## Scaffold 3D Fabrication by Injection Molding



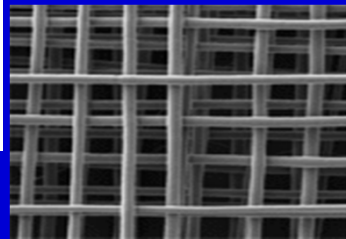
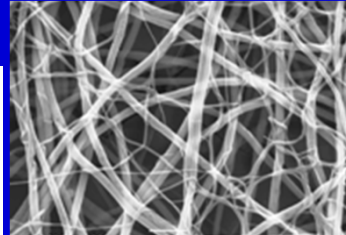
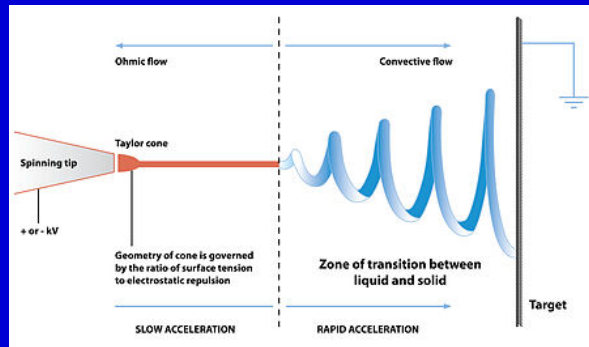
# Fused Deposition Modeling (Thermoplastic Extrusion)



# Fused Deposition Modeling

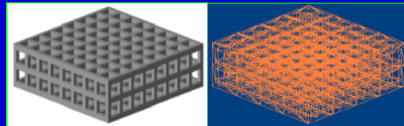


# Fiber Electrospinning

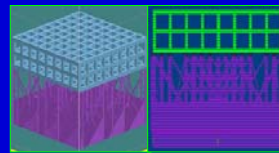


# Scaffold Fabrication by Stereolithography

Making model and STL file



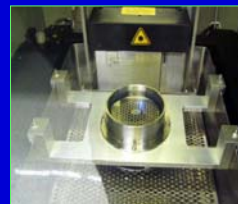
Making support and slicing



Post-processing and curing

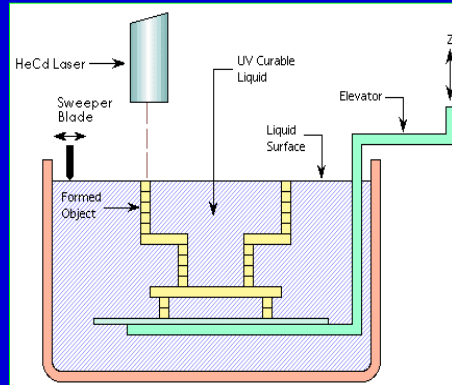


Photo-crosslinking in SLA

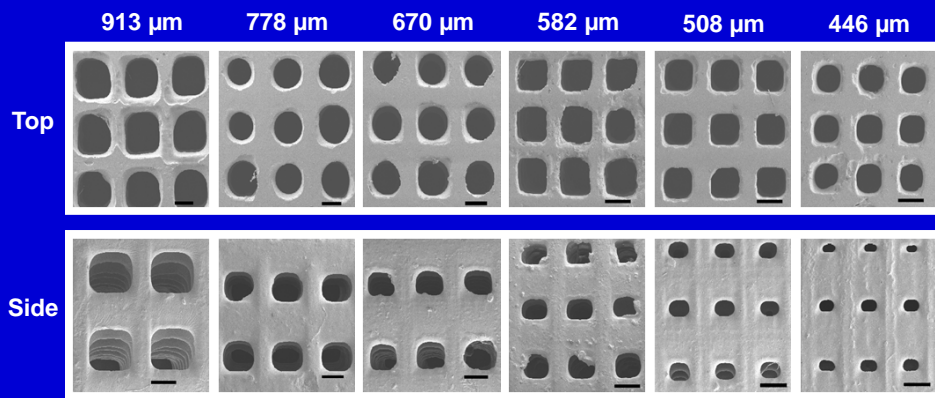


# Stereolithography (SLA)

- Layer-based fabrication technique using UV laser to polymerize resins



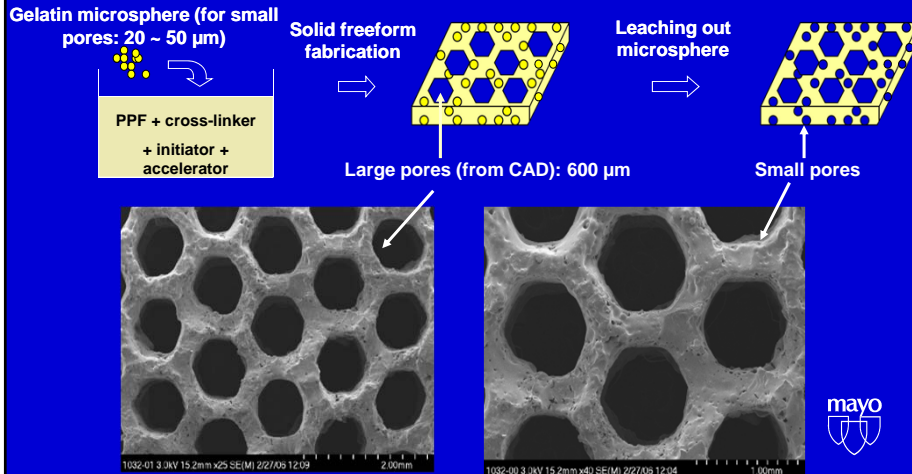
# Pore morphology (SEM)



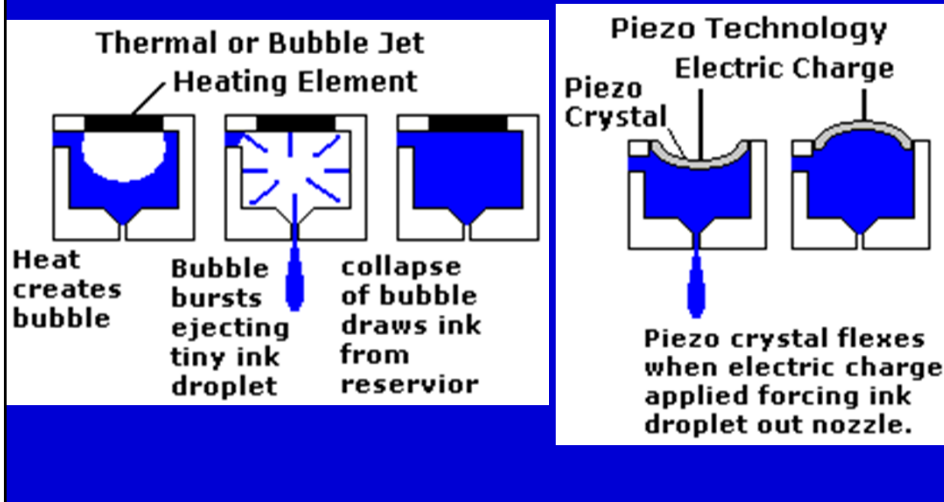
(\* Bar represents 400  $\mu\text{m}$ )



# Bimodal Porosity in Scaffold

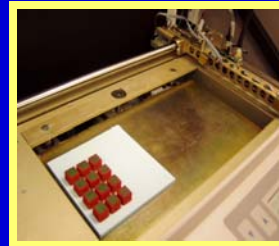


# Scaffold Fabrication by 3D Thermal or Piezo Inkjet Printing

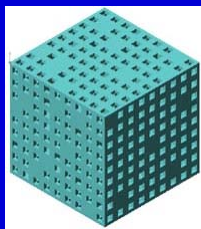


# Scaffold Fabrication by 3D Thermoplastic Inkjet Printing

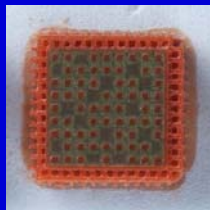
- One of the solid freeform fabrication (SFF) techniques
- Allows fabrication using any material that can be injected and then formed in situ
- The process exploits variations in solubility and thermal properties among the build materials



# Scaffold Fabrication by 3D Thermoplastic Inkjet Printing



CAD Design of Scaffolds With Defined Interconnectivity



Fabrication of CAD Designed Scaffolds by 3-D Microprinting

Removal of the Solid Phase by Solvent Dissolution

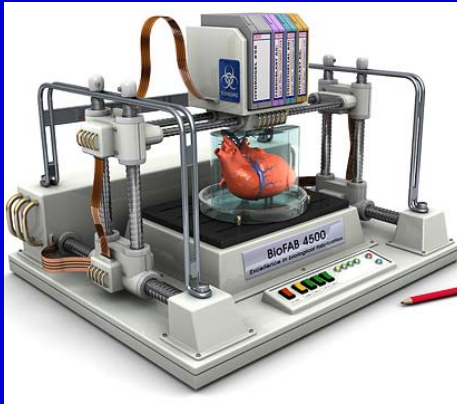


Injection of Degradable Crosslinkable Macromer in the Scaffold's Solid Phase

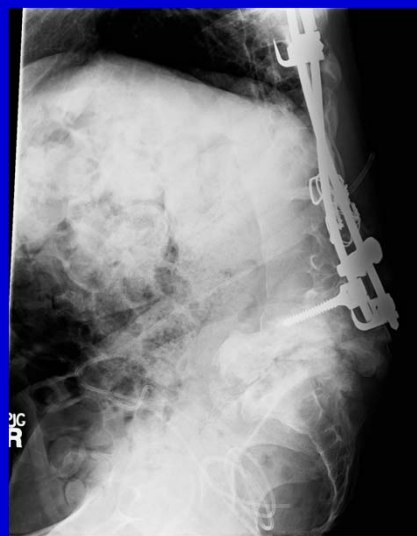


# Bioprinting

- Bio-ink: cells in aqueous solution for rheologic properties
- Bioscaffold (or “bio-paper”): surface for cell attachment and expression of matrix secretion
- Hydrogel for controlled delivery of cells & biomolecules



## 3D Printed Models for Surgical Planning and Intraoperative Guidance

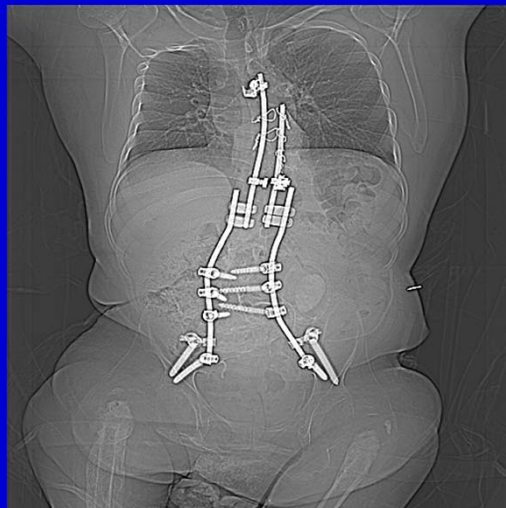
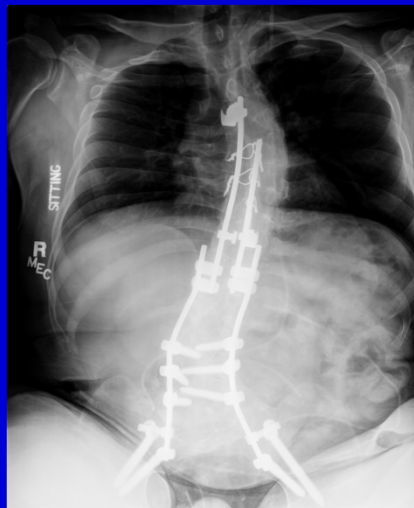


## Charcot Arthropathy with Spinopelvic Dissociation



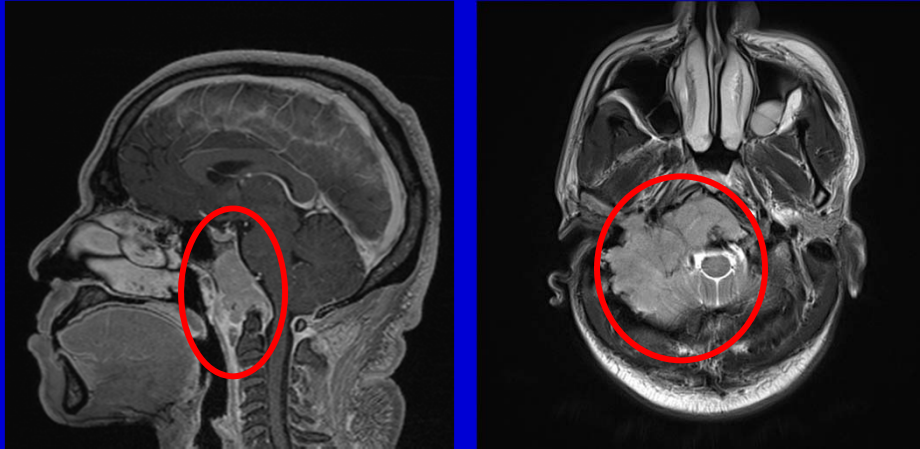
- 30 year old man with thoracic level paralysis and developmental delay
- 6 inch diameter ulcer with purulence at lumbosacral junction
- Poor sitting balance and further ulcer risk based on spinopelvic dissociation

## Charcot Arthropathy with Spinopelvic Dissociation



## POEMS Syndrome

---



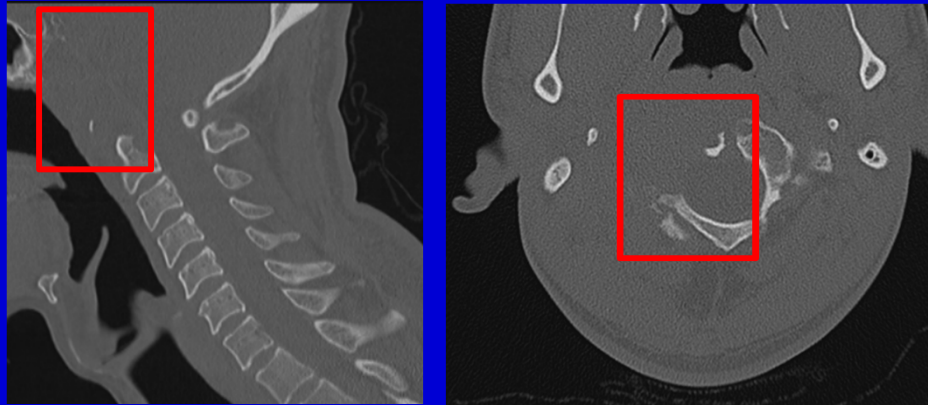
## POEMS Syndrome

---

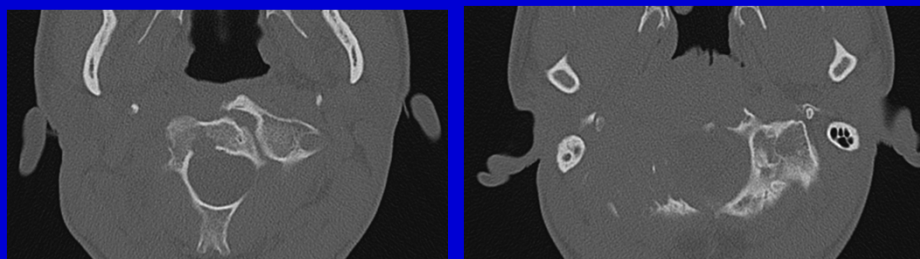
- **P**olyneuropathy
- **O**rganomegaly
- **E**ndocrinopathy
- **M**onoclonal Gammopathy
- **S**kin Changes



# POEMS Myeloma with Resorption of Skull Base and Upper Cervical Spine

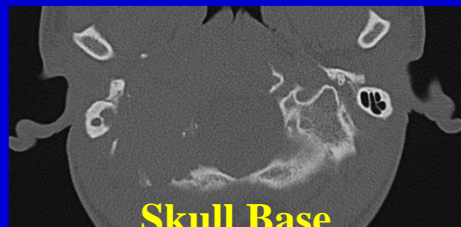


# POEMS Myeloma with Resorption of Skull Base and Upper Cervical Spine



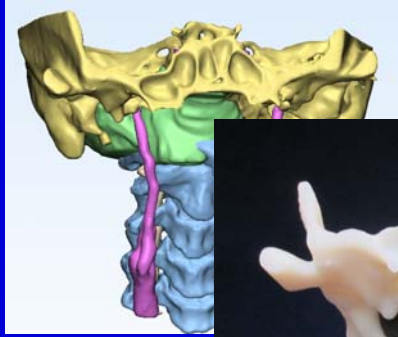
**C1 and C2**

**Foramen Magnum**



**Skull Base**





## Touch adds to comprehension

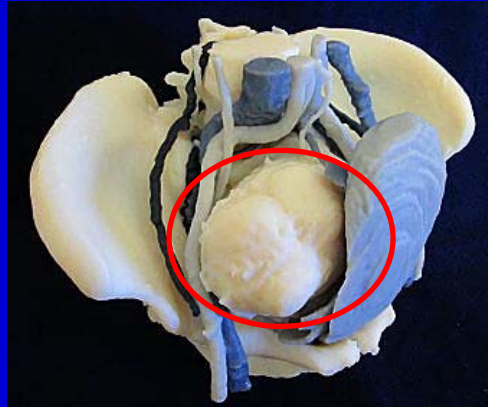


Three-dimensional printing permits greater understanding of complicated anatomy allowing surgeons to treat complex patients with greater safety & better outcomes.



## Patient Counselling: One model is worth a thousand words

---



## Teaching Anatomic Pathology: Supplement to cadavers

---



## The Future: Gaps

---

- Composite Tissue Regeneration
- Brain-Computer Interface linked to Tissue & Organ Regeneration
- Cells and Biomaterials in Single additive Manufacturing Implant



## The Future: Research Questions

---

- What are the pertinent biologic processes at the junctions between different tissue types, and how can we engineer them in 3D?
- Do we manufacture and implant a 3D tissue or organ, or do we manufacture and implant a bioreactor to induce the formation of the new tissue/organ *in vivo*?



# **Tendon and Ligament Tissue Engineering**

## **Clinical Needs:**

- Degenerative tendon tears
- Traumatic tendon and ligament injuries

## **Clinical Issues:**

- Musculotendinous junction
- Enthesis: tendon/ligament to bone junction
- Intrasynovial Environment



## **Composite Tissue Regeneration**

# **Tendon and Ligament Tissue Engineering**

## **• Current Treatment Options**

- Direct repair to bone (e.g. rotator cuff repair)
- Direct repair to muscle (e.g. tendo achilles repair to gastrocsoleus)
- Substitution (e.g. anterior cruciate ligament reconstruction via bone-tendon-bone patellar graft or semitendinosus graft)

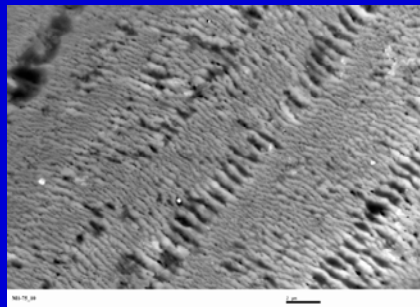


# Tendon and Ligament Tissue Engineering

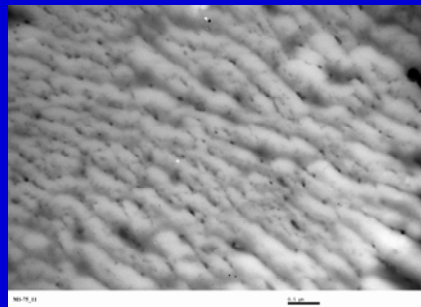
- Create scaffolds that resist tensile load
- Culture fibroblasts on scaffolds
- Deliver signaling molecules to fibroblasts that have attached to scaffolds
- Assess engineered tendon or ligament by collagen production and tensile mechanical strength



# Self-Assembled Block Copolymer Transmission Electron Microscopy



Low Magnification

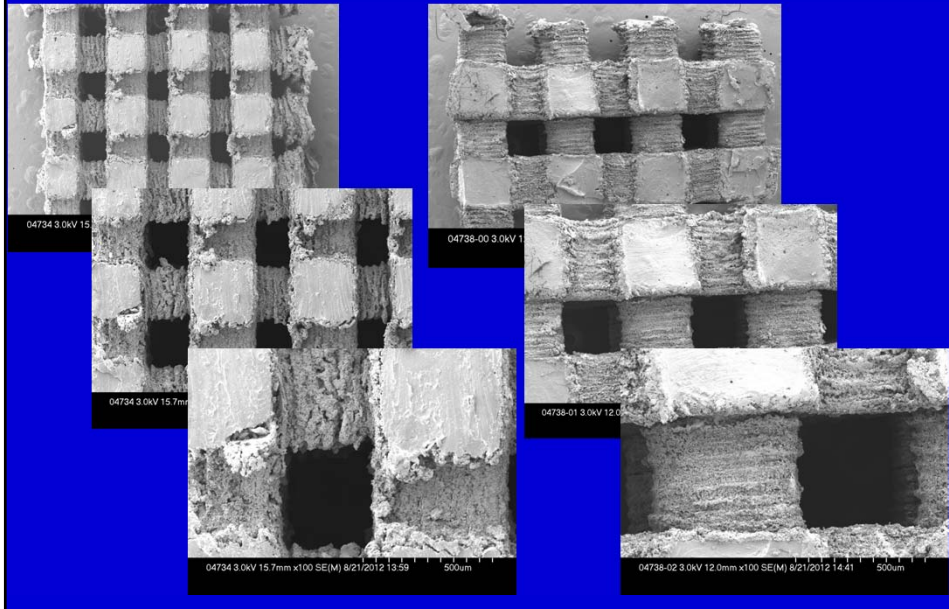


High Magnification

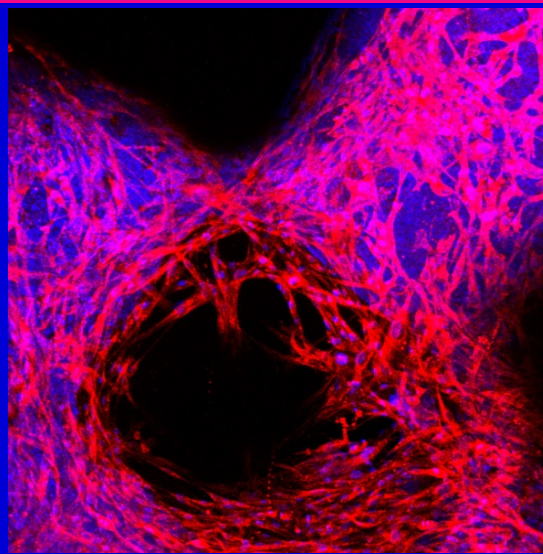
PCLF-co-PMMA, 82% PCLF



# Tendon/Ligament Scaffold SEM



## Collagen I Production on Fibroblast-Seeded Tendon/Ligament Scaffolds at 4 Weeks in Culture with Platelet Lysate and Fibroblast Growth Factor



# Acknowledgements

---



# Armed Forces Institute of Regenerative Medicine



# Acknowledgements

## Funding

- Mayo Foundation
- National Institutes of Health (R01 AR45871, R01 EB03060, R01 EB02390)
- Department of Defense
- Hulman-George Foundation



## The Team



