BML 300: INTRODUCTION TO HEALTHCARE ENGINEERING

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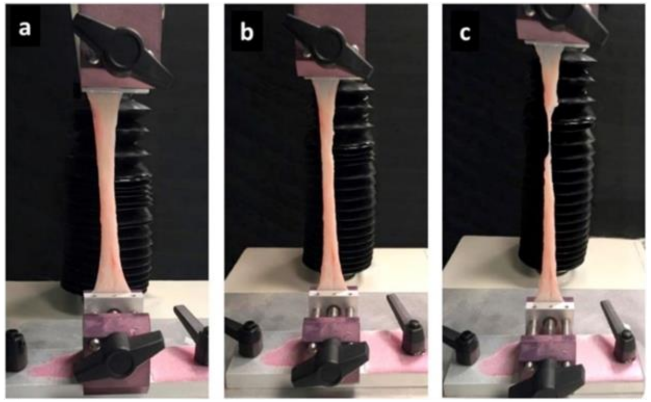
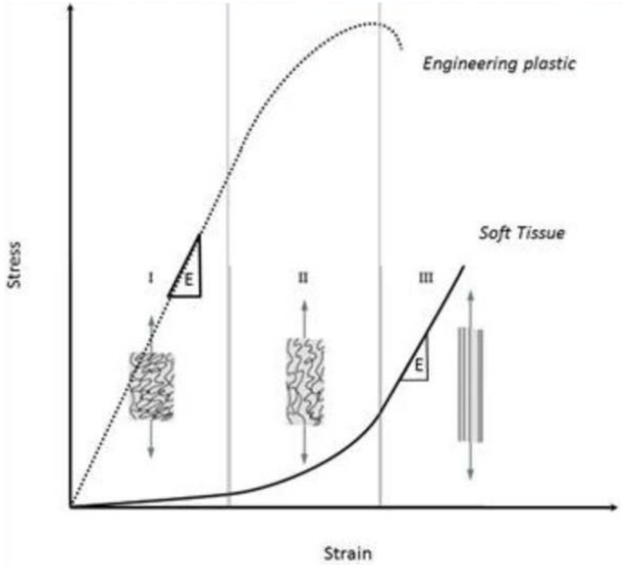
Biomechanical Properties: Uniaxial

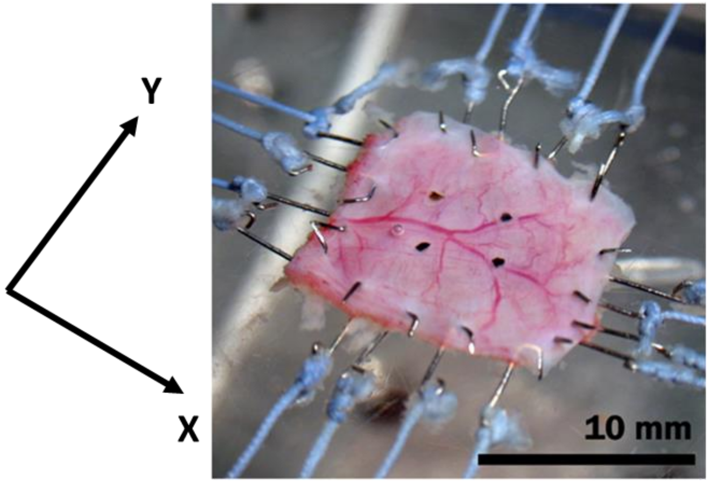
- A tissue specimen is clamped in a way that its length is parallel (longitudinal) to the direction of load application
- The bottom clamp is fixed
- The top clamp is displaced at a certain rate (i.e., displacement rate). It is alternatively called as strain rate
- After a certain point, beyond a certain strain, the tissue tends to rupture, and once the load drops significantly, the test stops.
- During the experiment, the fibers within the tissue stiffens, as it aligns more towards the load direction
- Pull force (load cell)→displacement (motor-screw)
- Stress=Force/Initial Area
- Strain=Change in length/Initial length
- Experimental data is generated by a Universal Testing Machine (UTM) at multiple locations during the test
- The Modulus of Elasticity (Slope=Stress/Strain) changes along the Stress-Strain plot

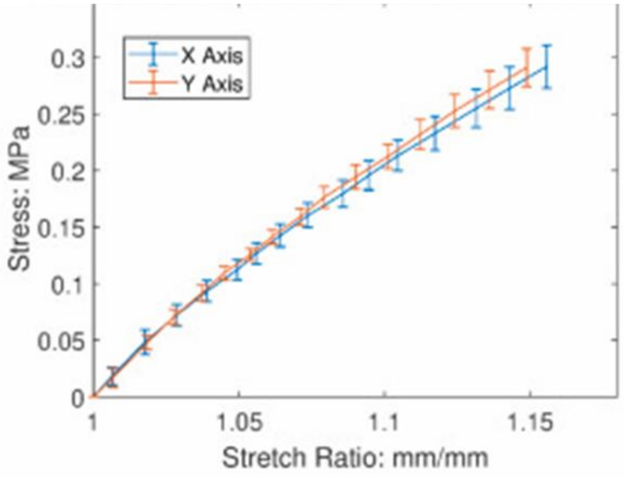




Biomechanical Properties: Biaxial

- A planar tissue specimen is clamped orthogonally in a way that load will be applied in both directions
- Along both directions, one side clamp will be fixed
- The clamps which are not fixed will be displaced at a certain rate (i.e., displacement rate) for equibiaxial loading or different rates for non-equibiaxial loadings. It is alternatively called as strain rate
- After a certain point, beyond certain strains, the tissue tends to rupture, and once the loads drop significantly, the test stops.
- During the experiment, the fibers within the tissue stiffens, as it aligns more towards the load directions
- Pull force (load cell)→displacement (motor-screw)
- Stress=Force/Initial Area
- Strain=Change in length/Initial length
- Experimental data is generated along the two axes by a Biaxial Testing Machine at multiple locations during the test
- The Modulus of Elasticity (Slope=Stress/Strain) changes along the Stress-Strain plot





Biomechanical Properties: Tissues

Tissue Name	Sub-group/ Remarks	Elastic modulus	Ultimate tensile strength	Shear modulus	Reference
Skin tissue	–	83.3 ±34.9 MPa	21.6 ±8.4 MPa	–	[49]
	parallel to the Langer lines	160.8 ±53.2 MPa	28.0 ±5.7 MPa	–	[36]
	perpendicular to the Langer lines	70.6 ±59.5 MPa	15.6 ±5.2 MPa	–	[36]
Muscle tissue	biceps brachii	–	–	17.9 ±5.5 kPa	[28]
	flexor digitorum profundus	–	–	8.7 ± 2.8 kPa	[28]
	soleus	–	–	12.5 ±7.3 kPa	[28]
	gastrocnemius	–	–	9.9 ±6.8 kPa	[28]
	skeletal muscle	–	–	27.8 ±5 kPa	[29]
	temporal muscle	1.58 ±0.64 MPa	0.26 ±0.11 MPa	–	[81]
Connective Tissues	tendons	1.0-1.5GPa	100-140MPa	–	[91,93]
	achilles tendon	0.8 GPa	–	–	[94]
	achilles tendon	0.87 ±0.2GPa	–	–	[254]
	achilles tendon	1.16 ±0.15GPa	–	–	[255]
	ligaments (knee)	3.75-4.3 GPa	–	–	[98,99]
	patellar ligament	225 MPa	–	–	[100]
	ankle ligaments	260 MPa	–	–	[101]

Biomechanical Properties: Tissues

Brain tissue	–	1-7 kPa	–	–	[141]
	white matter and gray matter	–	–	2.7 kPa and 3.1 kPa	[25]
	white matter and gray matter	–	–	1.01 kPa and 0.752 kPa	[113]
	white matter and gray matter	3.66± 0.12 kPa and 2.80 ± 0.14 kPa	–	–	[114]
	white matter and gray matter	1.89 ±0.59 kPa and 1.39 ±0.29 kPa	–	–	[115]
Nasal cavity	septal cartilage	1.39 MPa	–	–	[151]
	nasal periosteum	–	3.88 MPa	–	[153]
	alar cartilages	2.09 ±0.81 MPa	–	–	[152]
	septal cartilage	2.72 ±0.63 MPa	–	–	[152]
Oral cavity	gingiva	37.36 ±17.4 MPa	3.81 ±0.9 MPa	–	[154]
	hard palate	18.13 ±4.51 MPa	1.70 ±0.9 MPa	–	[154]
	buccal mucosa	8.33 ±5.78 MPa	1.54 ±0.5 MPa	–	[154]
	uvula	2.63 ±1.08 kPa	–	–	[155]
	soft palate	6.54 ±3.52 kPa	–	–	[155]
	soft palate	0.9975 ±0.48 kPa	–	–	[157]
	soft palate	–	–	2.42 kPa	[158]
Tongue	–	6 kPa	–	–	[156,163,164]
	–	15 kPa	–	–	[161]
	–	5.52 ±1.19 kPa	–	–	[155]
	–	–	–	2.68 kPa	[158]
Tonsils	–	4.56 ±2.41 kPa	–	–	[155]

Biomechanical Properties: Tissues

Oesophagus	–	–	1.2 MPa	–	[175]
	–	4-14 kPa	–	–	[176]
Lung tissue	alveolar wall	4.4-5.9 kPa	–	–	[256]
	–	1.96 ±0.13 kPa	–	–	[182]
	–	5 kPa	–	–	[183]
	–	6.1 ±1.6 kPa	–	–	[181]
	–	1.4 ±0.4 kPa	–	–	[181]
	–	3.4 ±0.4 kPa	–	–	[181]
Heart tissue	pulmonary valve	16.05 ±2.02 MPa	2.78 ±1.05 MPa	–	[185]
	aortic valve	15.34 ±3.84 MPa	1.74 ±0.29 MPa	–	[185]
	–	1.27 ±0.63 to 27.9 ±10.59 kPa	–	–	[186]
Breast tissue	glandular tissue	2-66 kPa	–	–	[200]
	adipose tissue	–	–	0.5-25 kPa	[200]
***5% precompression **20% precompression**	normal fat*	18 ±7 to 22 ±12 kPa	–	–	[190]
	glandular tissue*	28 ±14 to 35 ±14 kPa	–	–	
	fibrous tissue*	96 ±34 to 116 ±28 kPa	–	–	
	normal fat**	20 ±8 to 24 ±6 kPa	–	–	[190]

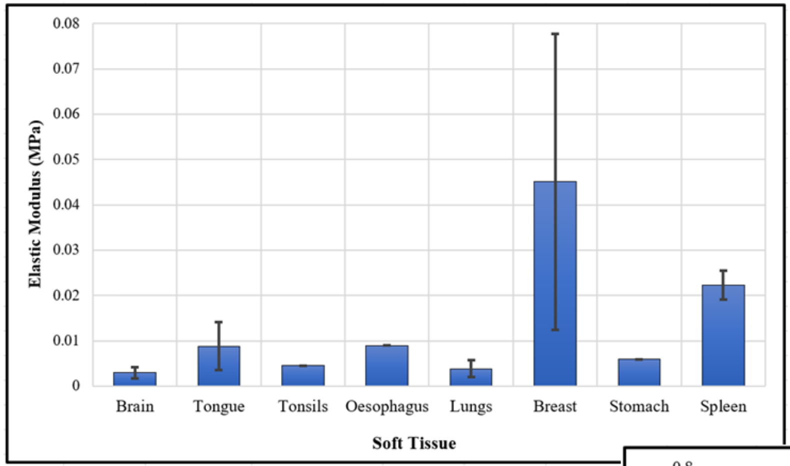
Biomechanical Properties: Tissues

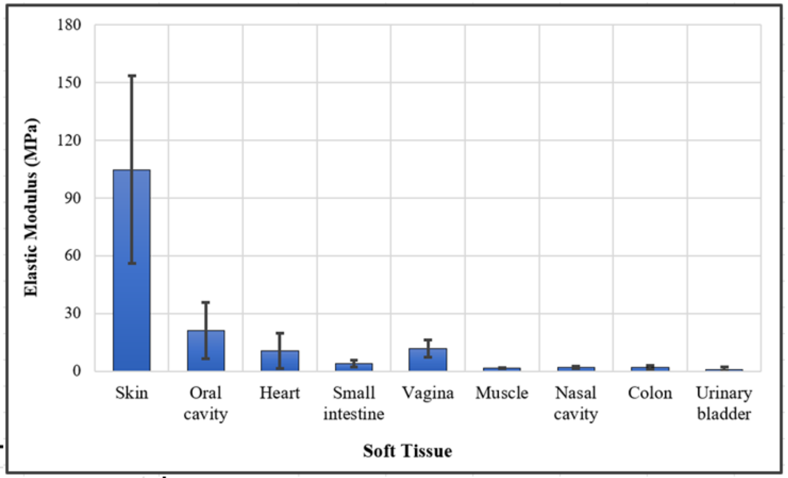
Liver tissue	tensile	10.5 kPa	–	–	[209]
	compressive	90 kPa	–	–	[210]
	compressive	66-386 kPa (male) 89-308 kPa (female)	203 kPa	–	[211]
	tensile	12.16 ±1.20 kPa	9.65 ±1.10 kPa	–	[208]
	compressive	196.54 ±13.15 kPa	314.01 ±19.10 kPa	–	[208]
	–	–	1.85 ±1.18 MPa	–	[204]
	–	270 kPa	–	–	[214]
Gallbladder	axial loading	641.20 ±28.12 kPa	1240 ±99.94 kPa	–	[216]
	transversal loading	255 ±24.55 kPa	348 ±66.75 kPa	–	[216]
Stomach	axial loading	–	0.7 MPa	–	[175]
	transversal loading	–	0.5 MPa	–	[175]
	–	5.93 kPa	–	–	[223]
Spleen	–	20 kPa	–	–	[211]
	–	24.5 ±6.4 kPa	–	–	[225]
Pancreas	–	–	–	1.65 kPa	[226]
Colon	dynamic loading	3.16 ±1.89 MPa	–	–	[228]
	intermediate loading	1.94 ±1.22 MPa	–	–	[228]
	quasi-static loading	1.19 ±1.23 MPa	–	–	[228]
	–	–	0.9 MPa	–	[175]
Small intestinal tissue	embalmed intestinal samples	5.16 ±3.03 MPa	–	–	[231]
	fresh intestinal samples	2.69 ±0.37 MPa	–	–	[231]
	–	–	0.9 MPa	–	[175]

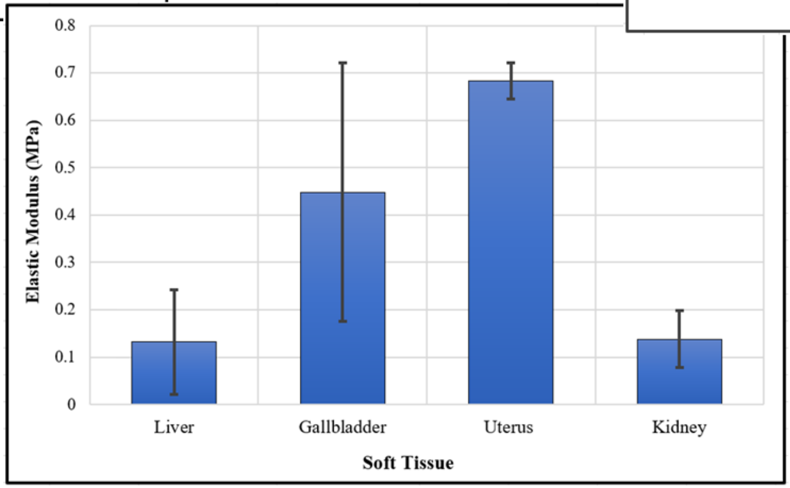
Biomechanical Properties: Tissues

Kidney tissue	capsular membrane	41.5 MPa	9.0 ±2.9 MPa	–	[233]
	axial direction	180.32 kPa	24.46 kPa	–	[234]
	transversal directions	95.64 kPa	31 kPa	–	[234]
Urinary bladder	–	0.25 MPa	0.27 MPa	–	[238]
	–	1.9 ± 0.2 MPa	0.9 ± 0.1 MPa	–	[239]
Uterus tissue	–	0.02-1.4 MPa	–	–	[242]
	–	656.3 ±483.9 kPa	–	–	[245]
	cervix	2.17-243 kPa	–	–	[242]
	anterior cervical lip (mid-term pregnancy)	80 kPa	–	–	[246]
	anterior cervical lip (full-term pregnancy)	30 kPa	–	–	[246]
	posterior cervical lip (mid-term pregnancy)	90 kPa	–	–	[246]
	posterior cervical lip (full-term pregnancy)	70 kPa	–	–	[246]
	cardinal ligament	0.5-5.4 MPa	–	–	[242]
	round ligament	9.1-14.0 MPa	4.1 MPa	–	[242]
	uterosacral ligament	0.75-29.8 MPa	4 MPa	–	[242]
Vaginal tissue	postmenopausal	14.35 MPa	–	–	[249]
	premenopausal	11.5 MPa	–	–	[249]
	–	5.8 ±1.3 MPa	2.4 ±0.7 MPa	–	[251]
	–	2.5-30 MPa	–	–	[242]

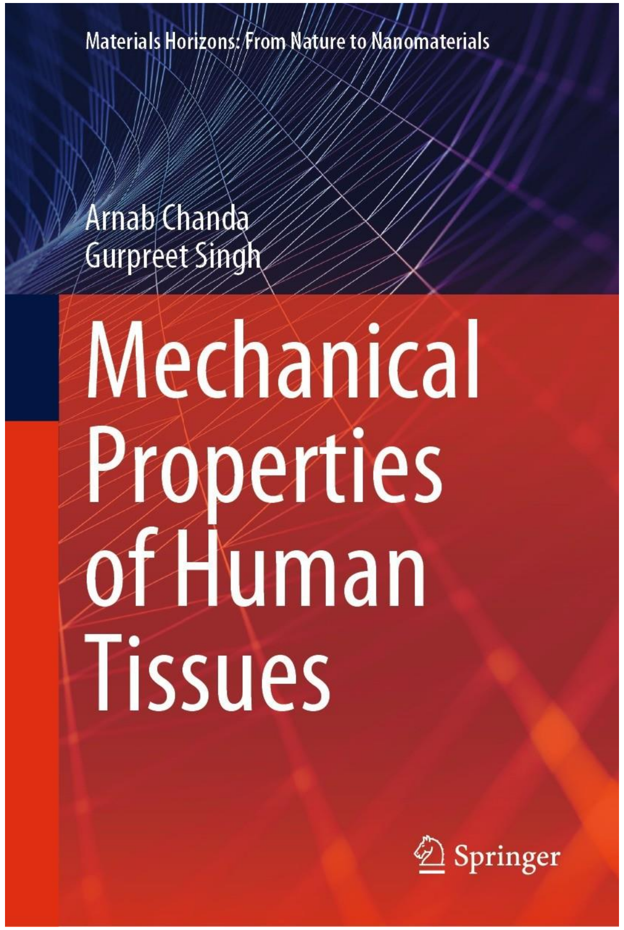
Biomechanical Properties: Tissues

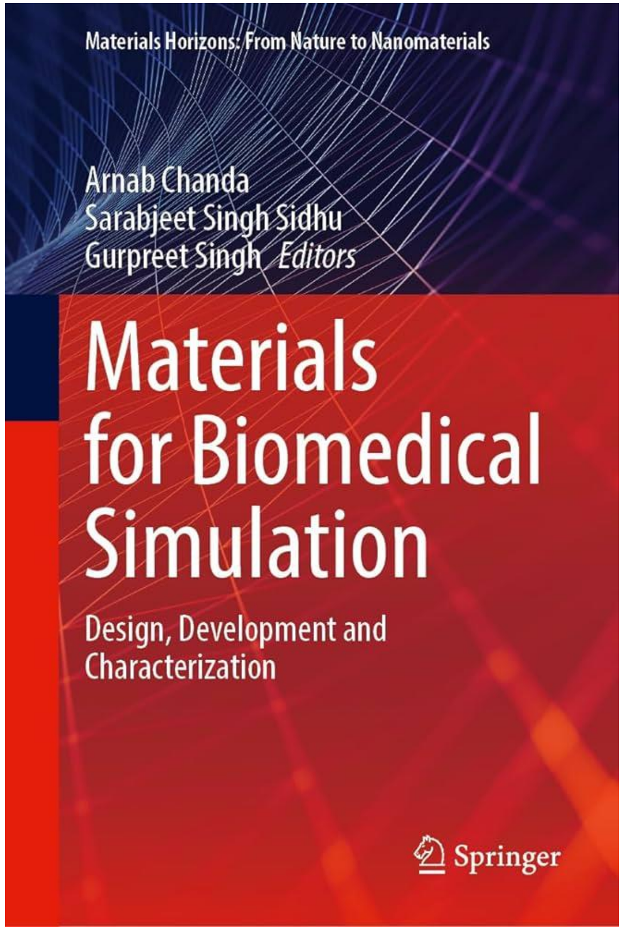






REFERENCE BOOKS





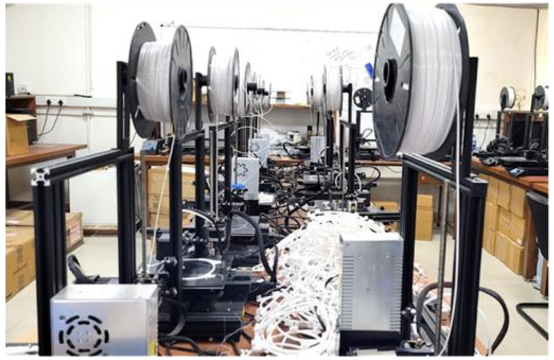
NEED FOR ARTIFICIAL TISSUES

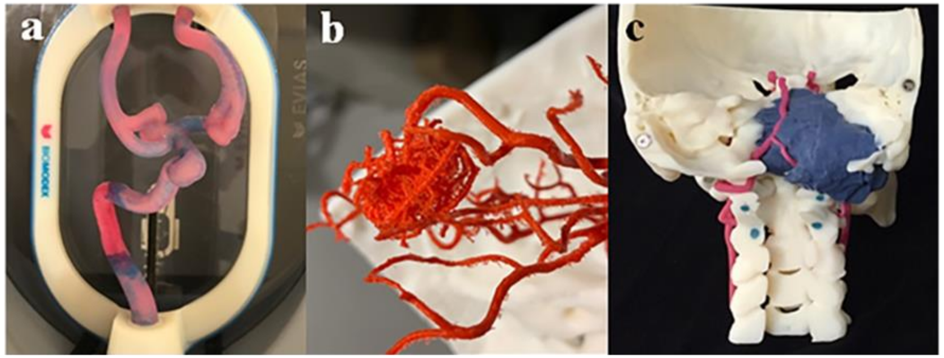
- Need for Realistic Testing
  - Huge demand for surgical and ballistic testing
  - Cadavers and live human tests pose ethical and biosafety issues
- Need for Artificial Tissues with:
  1. Material properties similar to natural tissue
  2. Surface properties (feel) similar to natural tissue
  3. Biosafety
  4. Low-cost priced for developing countries (i.e., India)

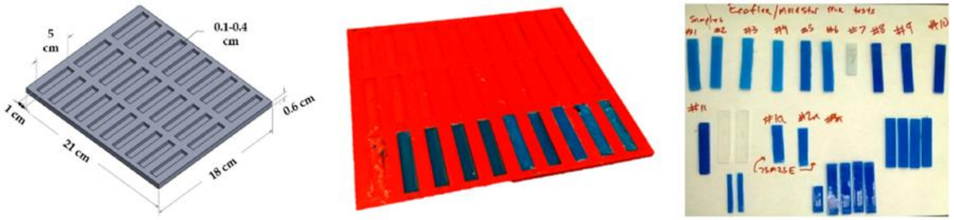
APPLICATIONS OF ARTIFICIAL TISSUES

ARTIFICIAL TISSUE-ORGAN DEVELOPMENT

- Role of 3D Printing
  - Development of complex moulds for tissue and organ fabrication
  - Fabrication of fixtures for experimental tests



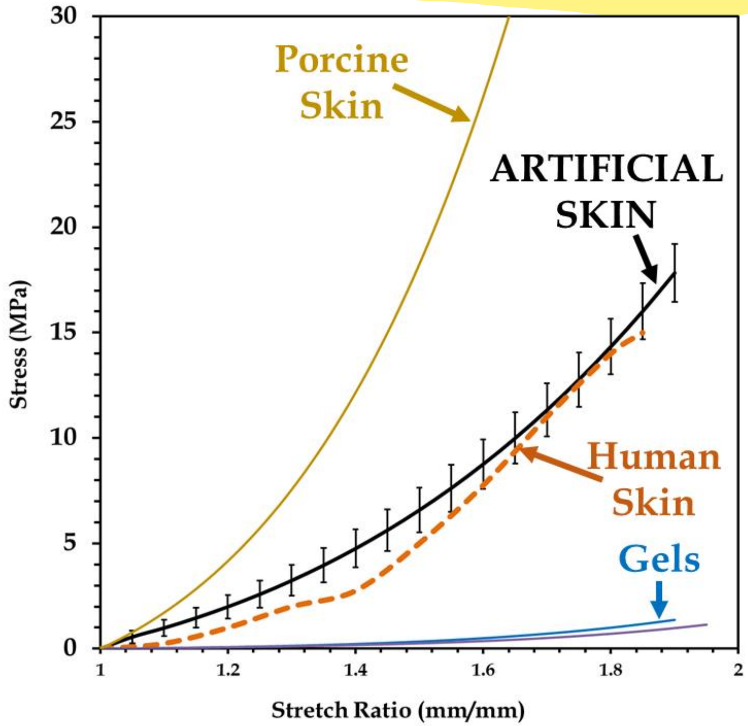




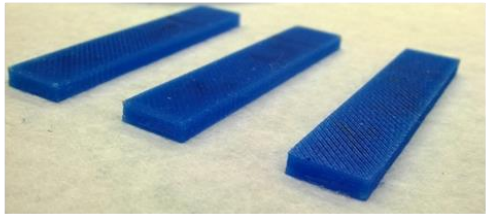
(a) (b) (c)

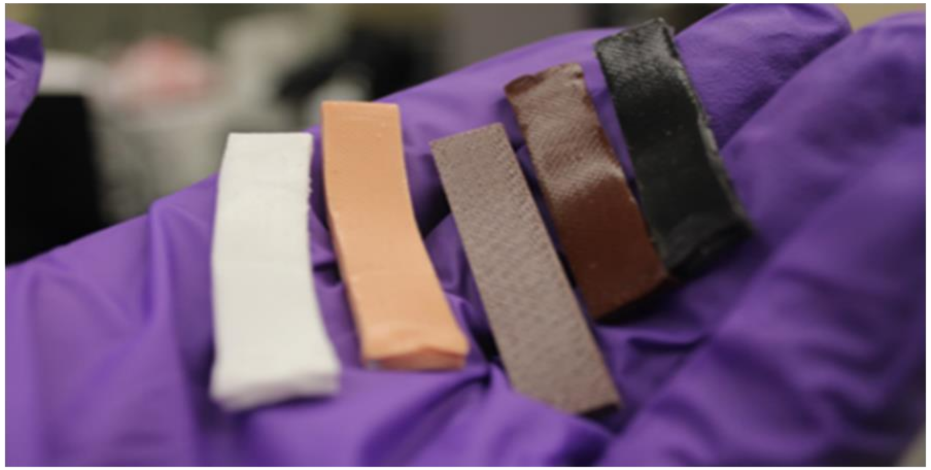
ARTIFICIAL SKIN

- No surrogate to date which can mimic the anisotropic mechanical properties of human skin
  - ***Porcine skin, cowhide, polyurethane, gels or cadavers*** *(tissue changes)*
- Mechanical property changes from one location to another



Skin surrogate comparison with other simulants



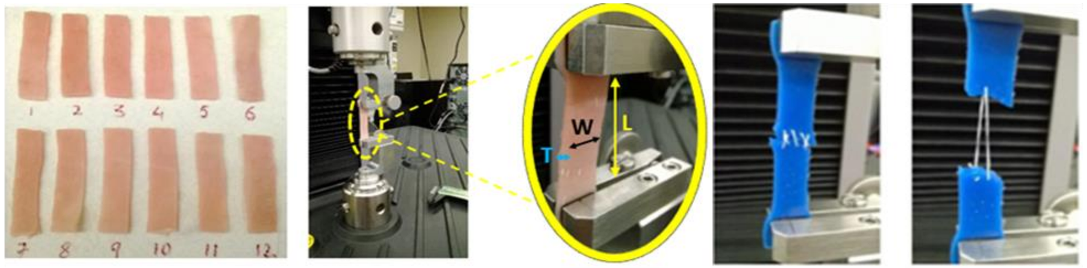


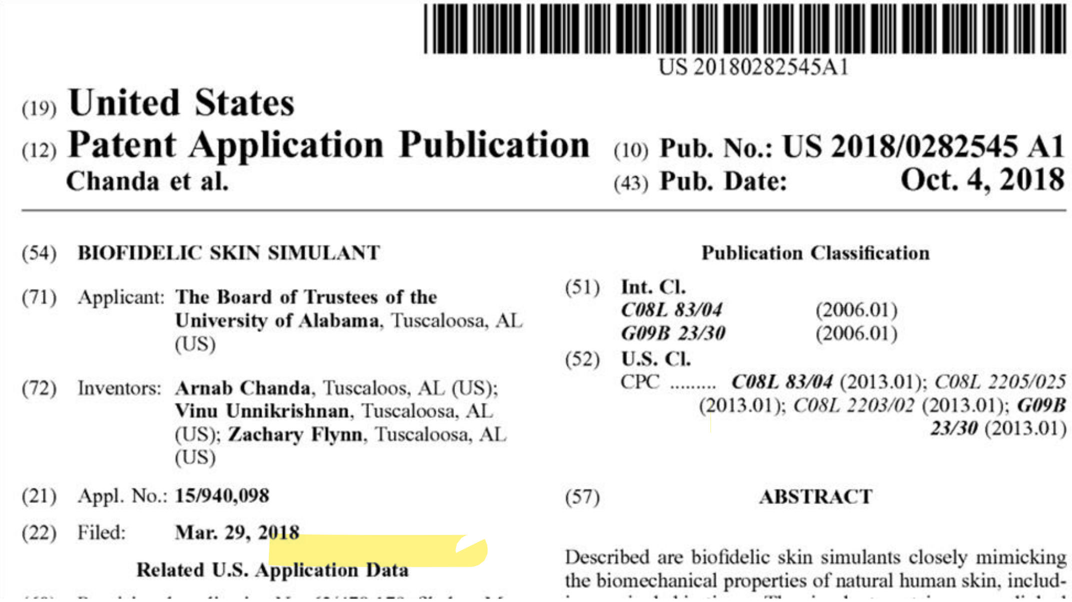
SYNTHETIC ARTIFICIAL SKIN

Chanda, Arnab, Vinu Unnikrishnan, and Zachary Flynn. "**Biofidelic skin simulant**." U.S. Patent No. US10049601B2.

SYNTHETIC ARTIFICIAL SKIN

1. **Match human skin properties** with a low-cost mass producible material
2. **Used in wound-suture experiments**
   - Standardize suturing practices
     - Determine suture forces for surgeries
     - Determine suture forces for robotic surgery
3. **Training on suturing practices** for different wound sizes and shapes, mold and skin tag removal





US 20180282545A1

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(12) **Patent Application Publication**
Chanda et al.

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(43) **Pub. Date: Oct. 4, 2018**

(54) **BIOFIDELIC SKIN SIMULANT**

(71) Applicant: **The Board of Trustees of the University of Alabama**, Tuscaloosa, AL (US)

(72) Inventors: **Arnab Chanda**, Tuscaloos, AL (US); **Vinu Unnikrishnan**, Tuscaloosa, AL (US); **Zachary Flynn**, Tuscaloosa, AL (US)

(21) Appl. No.: **15/940,098**

(22) Filed: **Mar. 29, 2018**

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G09B 23/30 (2006.01)

(52) **U.S. Cl.**
CPC *C08L 83/04* (2013.01); *C08L 2205/025* (2013.01); *C08L 2203/02* (2013.01); *G09B 23/30* (2013.01)

(57) **ABSTRACT**

Described are biofidelic skin simulants closely mimicking the biomechanical properties of natural human skin, includ-

SYNTHETIC ARTIFICIAL SKIN

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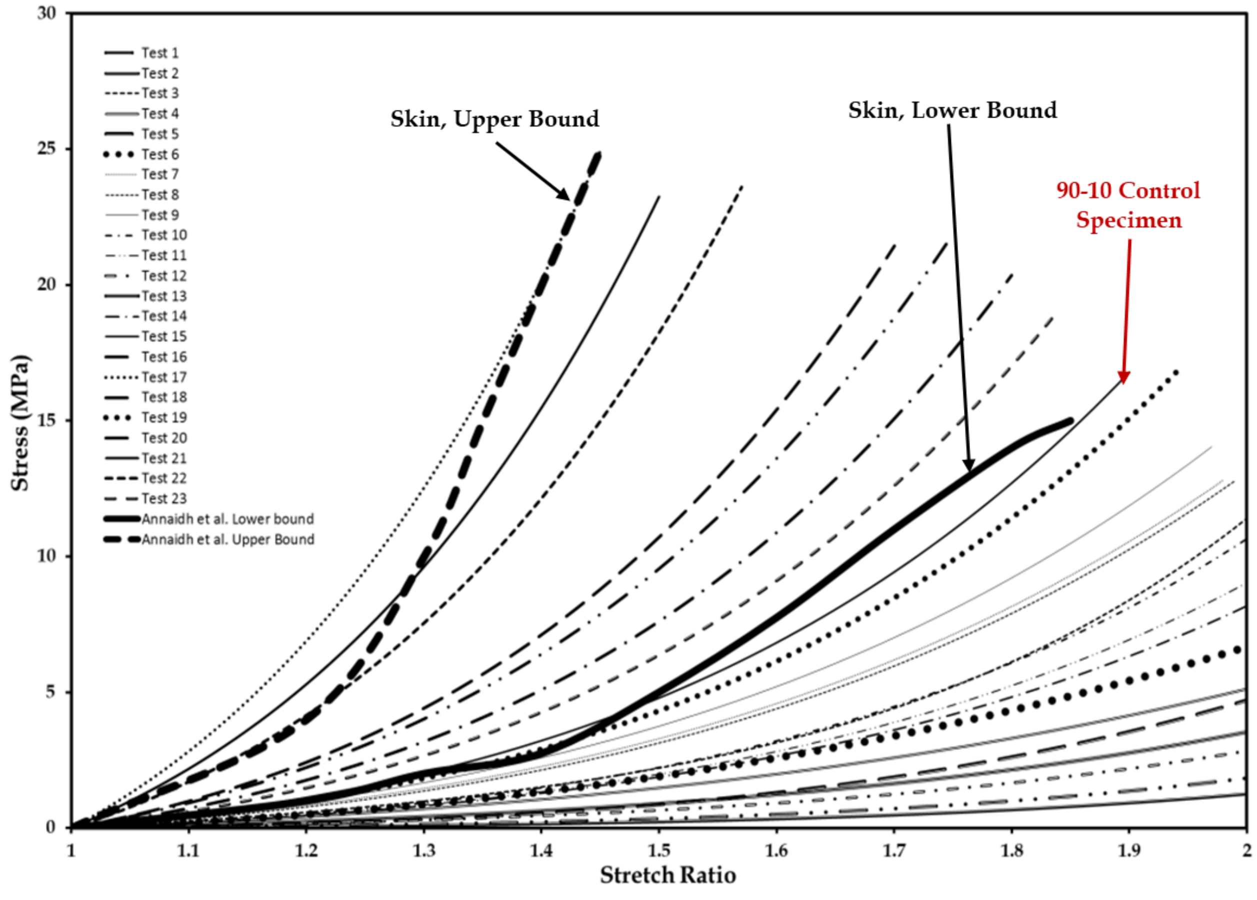
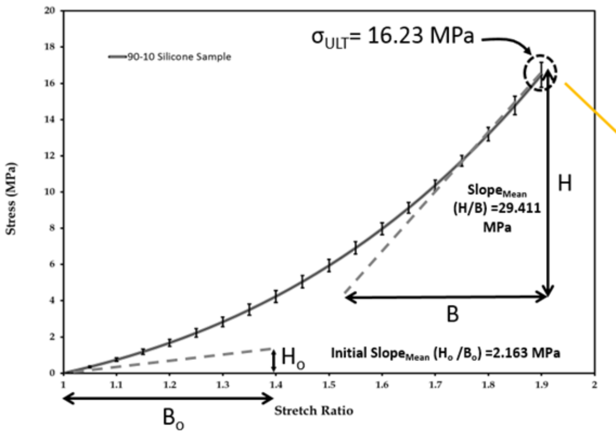
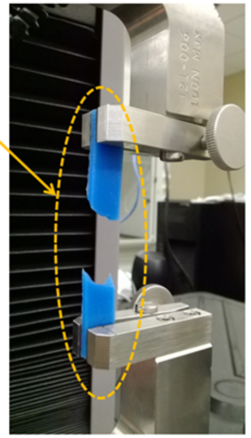


Synthetic Artificial Skin Compositions and Natural Skin Upper and Lower Bounds

Control 90-10 Test Specimen

1) Repeatability tests
2) Similar low and high strain modulus
3) Similar ultimate tensile stress
4) Similar non-linear behavior





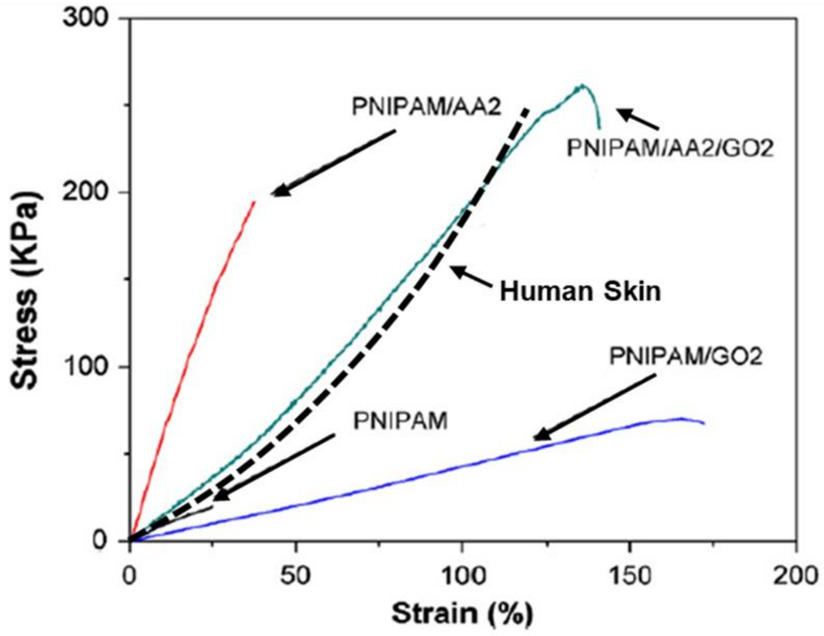
Control 90-10 Test Specimen Mechanical Properties

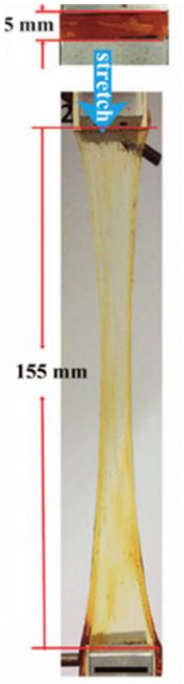
Chanda, Arnab, Vinu Unnikrishnan, and Zachary Flynn. "**Biofidelic skin simulant**." U.S. Patent No. US10049601B2.

HYDROGEL BASED ARTIFICIAL SKIN

- **Another type: Hyrogel Based Synethetic Skin**

•Using porous hydrogels with feel similar to natural tissues
•Hydrogel composition optimized to obtain skin mechanical properties





COST BREAKUP

(10 *10 *0.4 cc) Skin or 40 cc Hydrogel (density of 0.1-1 g/cc) = 40g (Max. mass)

Cost Breakup of Major Raw Materials:

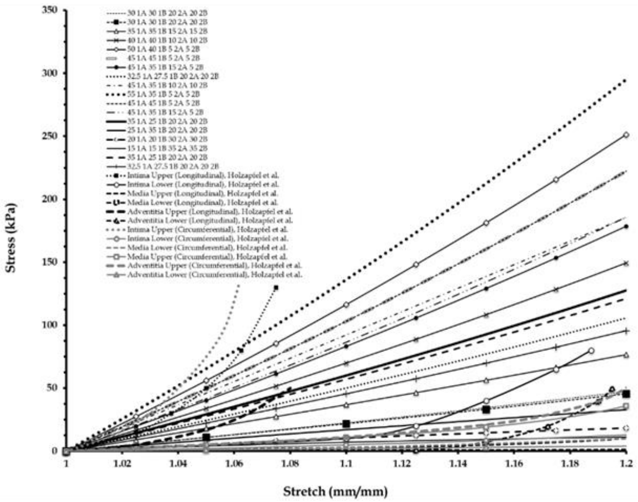
poly(N-isopropylacrylamide) (PNIPAM)=0.1 g (Rs. 29); polyacrylic acid (PAA) =1 g (Rs. 4); graphene oxide (GO)=0.2 g (Rs. 6); Distilled water=34.5 g (Rs. 5); Other chemicals/supplies= Rs. 3

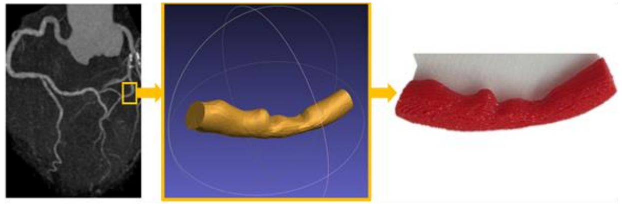
Total Cost: Rs. 47

40 cc Hydrogel=93.2 g silicone (density=2.33 g/cc)=Rs. 500/Kg equivalent of Silicone

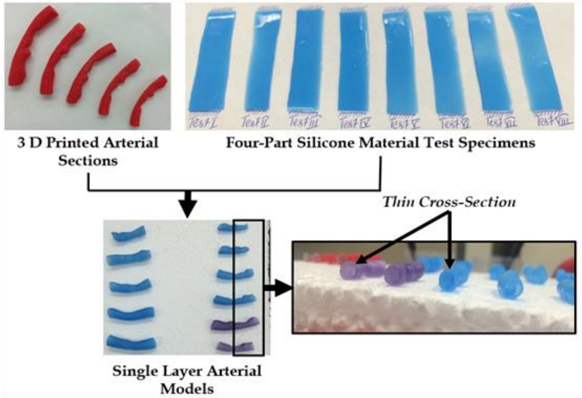
ARTIFICIAL ARTERY

- Patient-Specific 3 layer human artery surrogates
- **Fabrication Methodology**
  - Four-part silicone mixed in different ratios
    - Simulating 3 layers (*Intima, Media and Adventitia*)
    - Mechanically tested uniaxially
  - MRI images to 3D printed arterial section
  - Timed control dipping technique for layer thickness control

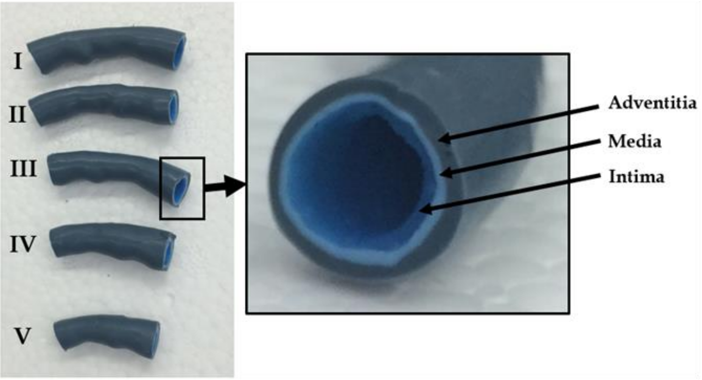




MRI Image to Artery Section



Single Layer Artery Model



3 Layer Artificial Artery

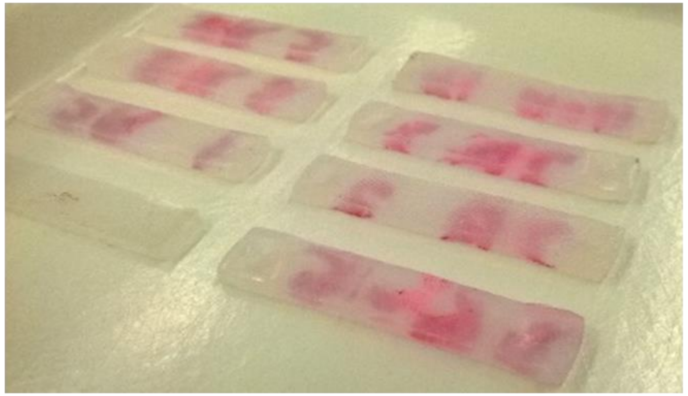
Chanda, Arnab, and Kaitlyn Curry. "**Patient-specific biofidelic human coronary artery surrogates.**" Journal of Mechanics in Medicine and Biology 18.05 (2018): 1850049.

ARTIFICIAL BRAIN TISSUE

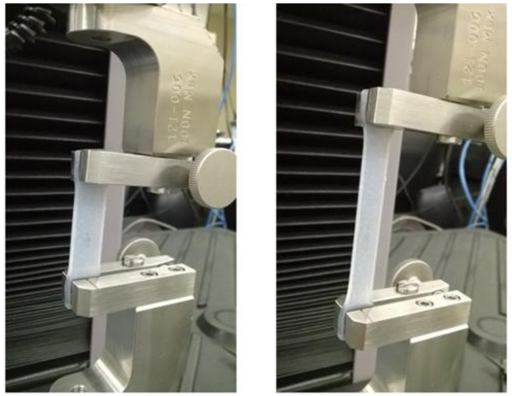
- No surrogate to date which can mimic the mechanical properties of Brain Tissue (*Grey and White Matter*)

- ## Fabrication Methodology
  - Two-part silicone mixed in different ratios
    - Two parts with shore hardness 00-10
  - 85 test coupons tested

- ## Mechanical Testing
  - Specimen size: Length=50 mm, Width= 10 mm, Thickness=1-4 mm
  - Varying Strain Rates: Low (2.5 mm/s) and High (30 mm/s)



Brain Tissue Composites

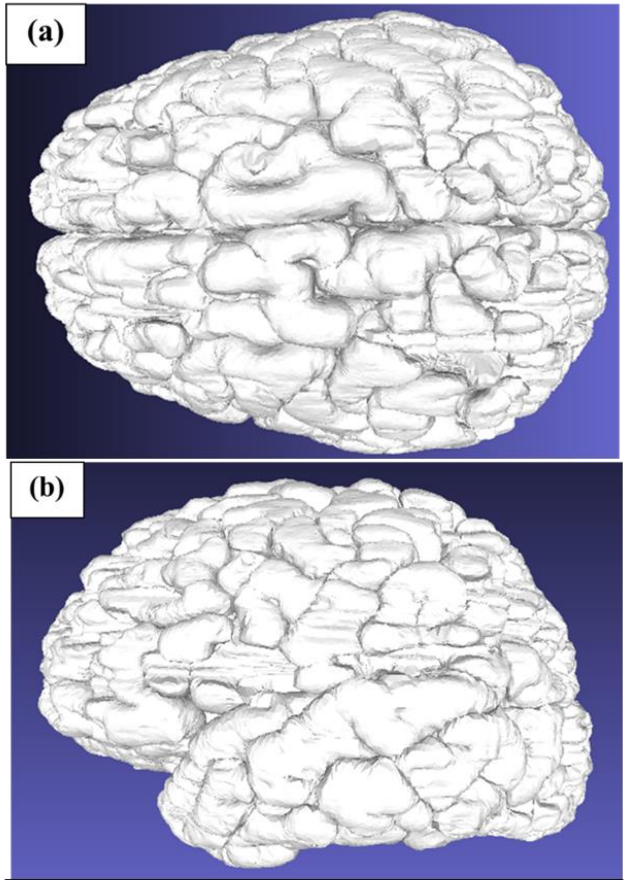


Tensile Tests

Chanda, A., Callaway, C., Clifton, C., & Unnikrishnan, V. **"Biofidelic human brain tissue surrogates."** Mechanics of Advanced Materials and Structures, (2016): 1-31.

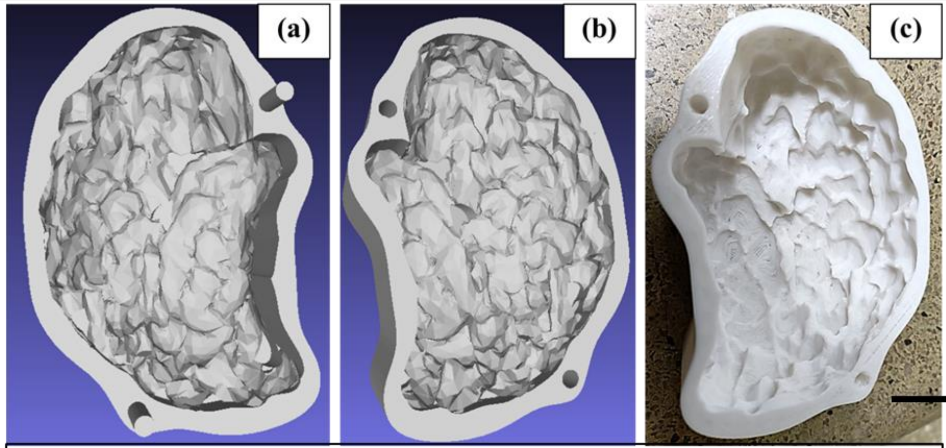
Testing of Artificial Brain Tissue

- Traumatic Brain Injuries (TBI) due to blast exposure or head impacts in contact sports, accidents are one of most critical research area. But the area of TBI is poorly investigated due to the limitation of brain tissue availability and related ethical/biosafety issues.
- In general, the brain tissue is difficult to acquire after the autopsy and test in laboratorial settings. To tackle this issue, full-size human brain simulant was developed using two-part polymeric material.
- Based on the number of mild to moderate traumatic brain injury cases reported in the literature, three TBI prominent locations were chosen i.e., prefrontal cortex of frontal lobe, top portion of parietal lobe and temporal lobe of right hemisphere of the brain.

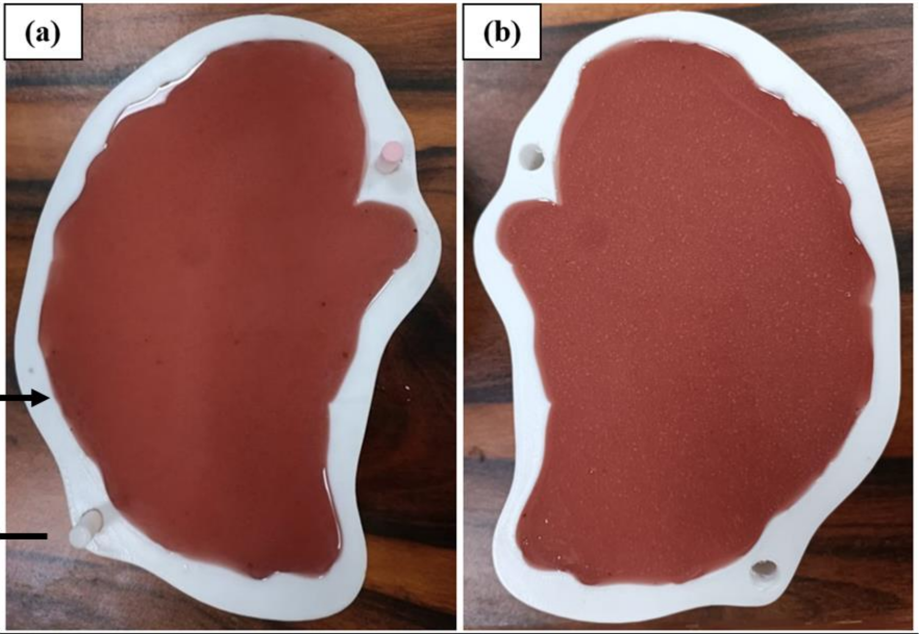


Full-sized brain model from MRI scan: (a) top view (b) side view.

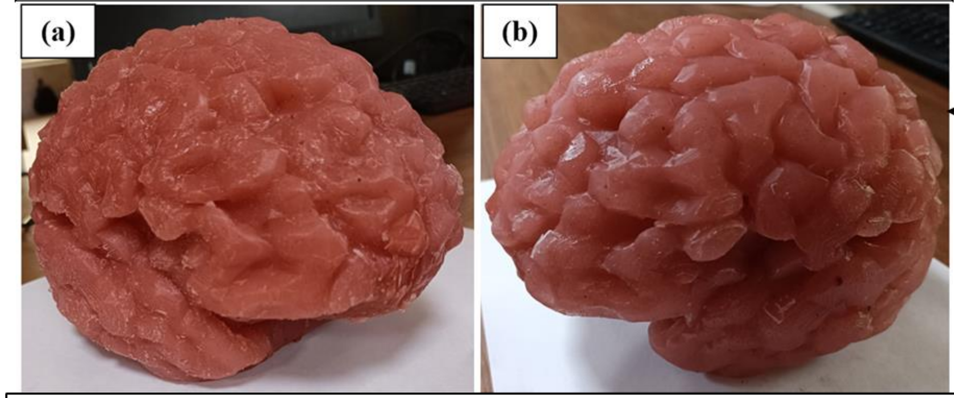
Testing of Artificial Brain Tissue



Negative molds in SolidWorks for 3D printing (a) Left half-mold (b) Right half mold (c) 3D printed right half mold using PLA.



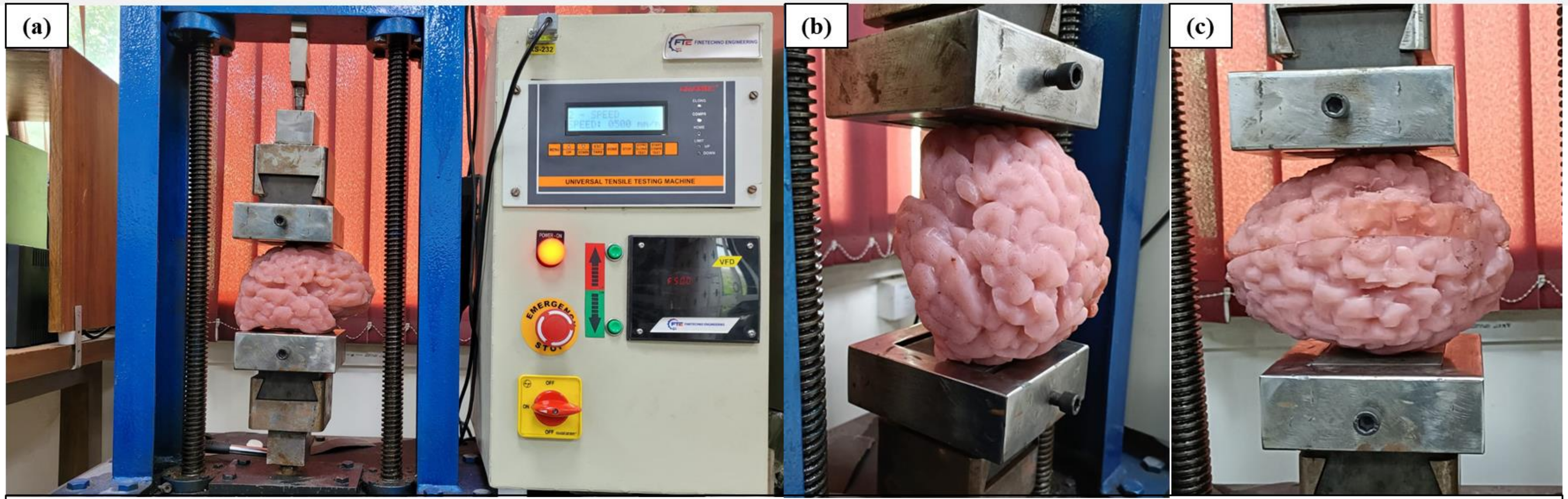
Polymeric mixture poured in: (a) Left half , and (b) Right half mold.



Final brain simulant: (a) Left side (b) Right side of the brain simulant.

Fabrication of Full-Scale Brain Model

Testing of Artificial Brain Tissue



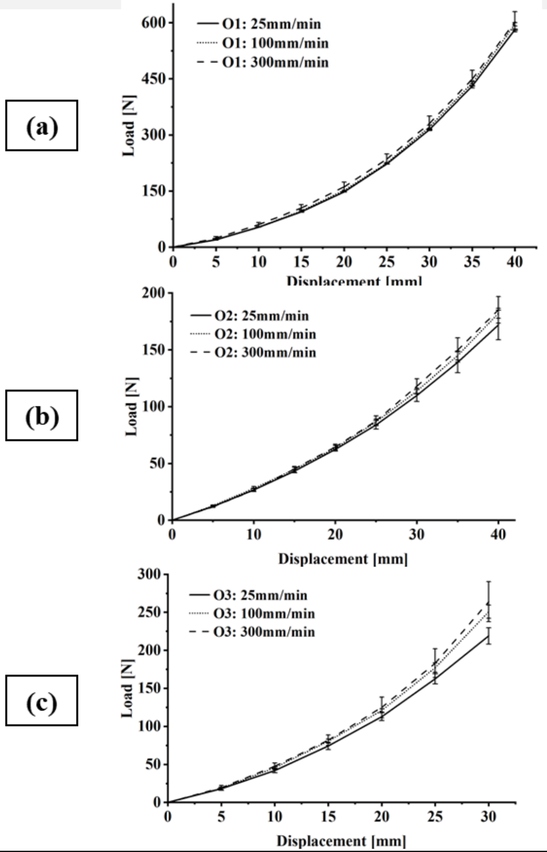
Compression tests on the brain simulant at three different locations: (a) Top portion of the parietal lobe (O1), (b) Prefrontal cortex of the frontal lobe (O2), and (c) Temporal lobe (O3).

Table. *Cross-sectional area details for the three tested locations.*

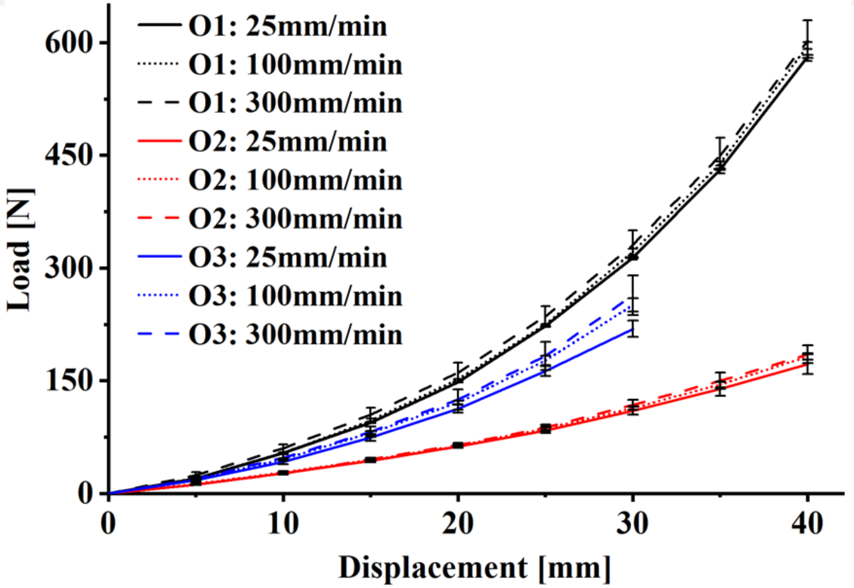
Locations	Length (mm)	C/S area (mm^2)	Strain rate (s^{-1}) (25 mm/min)	Strain rate (s^{-1}) (100 mm/min)	Strain rate (s^{-1}) (300 mm/min)
O1	121	19933.08	0.0035	0.0139	0.0417
O2	180	13411.03	0.0024	0.0096	0.0285
O3	133	16834.4	0.0032	0.0129	0.0384

Mechanical Testing of Full-Scale Brain Model

Testing of Artificial Brain Tissue



Load-Displacement plot for the brain simulant for three different loading rates at (a) top portion of the parietal lobe (O1), (b) prefrontal cortex of the frontal lobe (O2), and (c) temporal lobe (O3).



Load-Displacement plot for the brain simulant at three different locations for three different loading rates.

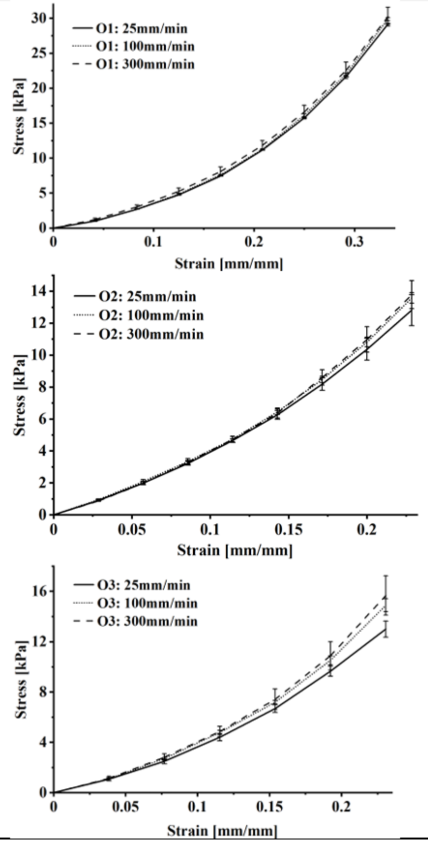
Brain Deformation upon Loading

Testing of Artificial Brain Tissue

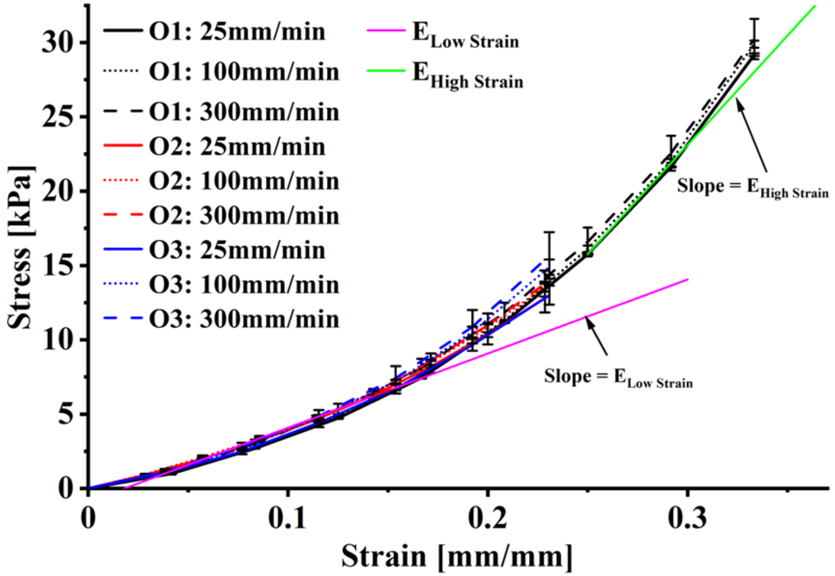
(a)

(b)

(c)



Stress vs Strain plot for the brain simulant for three different loading rates at (a) top portion of the parietal lobe (O1), (b) prefrontal cortex of the frontal lobe (O2), and (c) temporal lobe (O3).

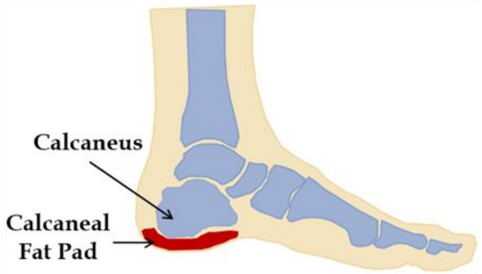


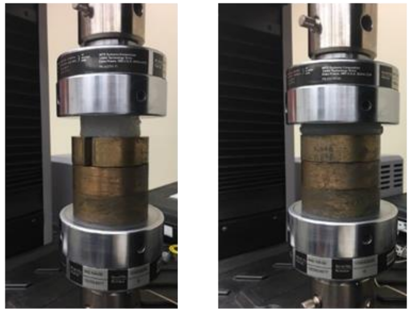
Stress vs Strain plot for the brain simulant at three different locations for three different loading rates along with linear curve fit at low strain and high strain range.

Stress-Strain Plots

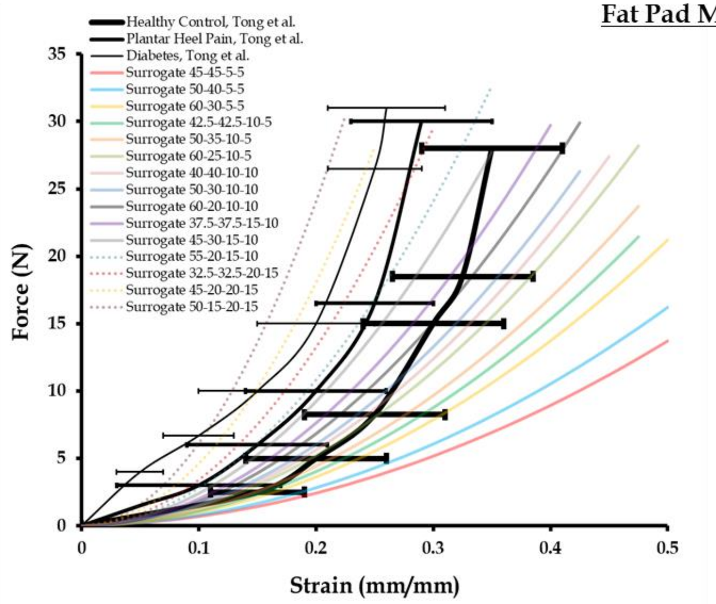
ARTIFICIAL NORMAL/DISEASED CALCANEAL FAT PAD

- **Fabrication Methodology**
  - Four-part silicone (0010 and 30A) mixed in different ratios
- **Mechanical Testing**
  - Specimen size: Diameter=60 mm, Depth=18 mm, Thickness=1-4 mm
  - Tests:
    - Strain rates (0.80 mm/s, 1.96 mm/s)
    - Cyclic strain rate (1.96 mm/s)
    - High Strain Rates (180-1800 mm/s)
- **Tissues Simulated**
  - Healthy Fat Pad
  - Diseased Fat Pad (Diabetes)
  - Diseased Fat Pad (Plantar Fasciitis)





Fat Pad Mechanical Tests

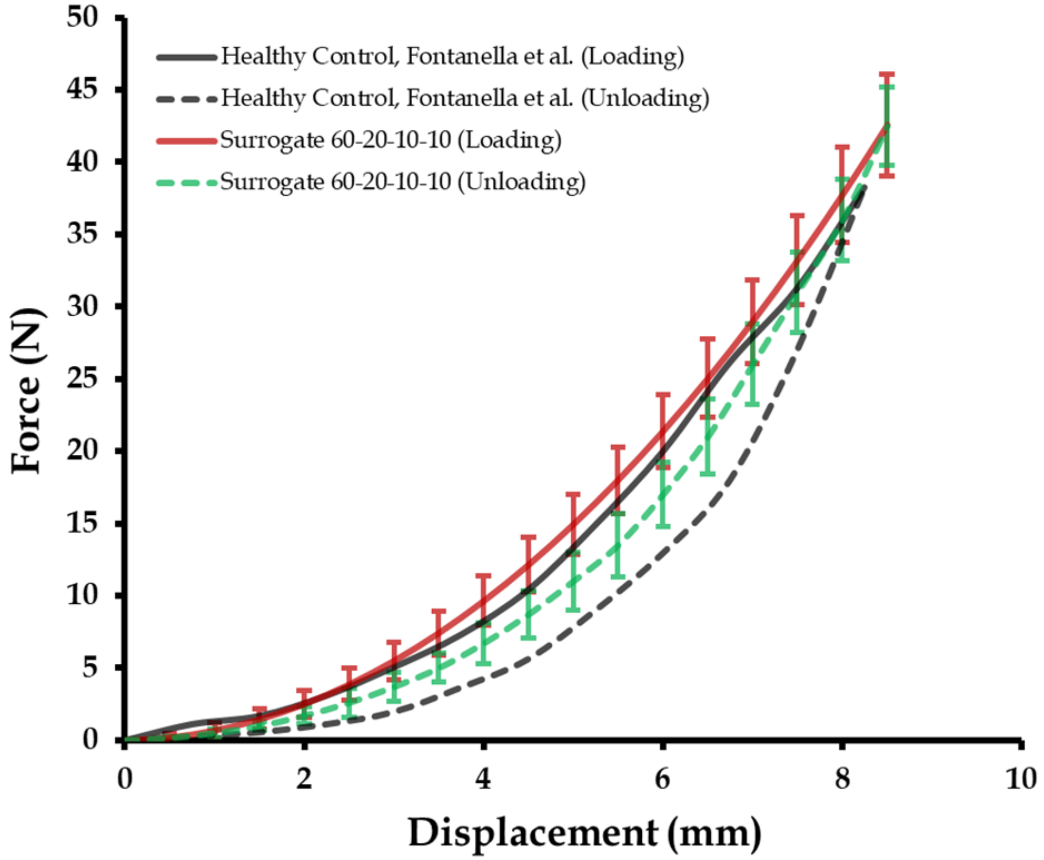


Fat Pad Surrogates compared with Healthy and Diseased Fat Pad Tissues

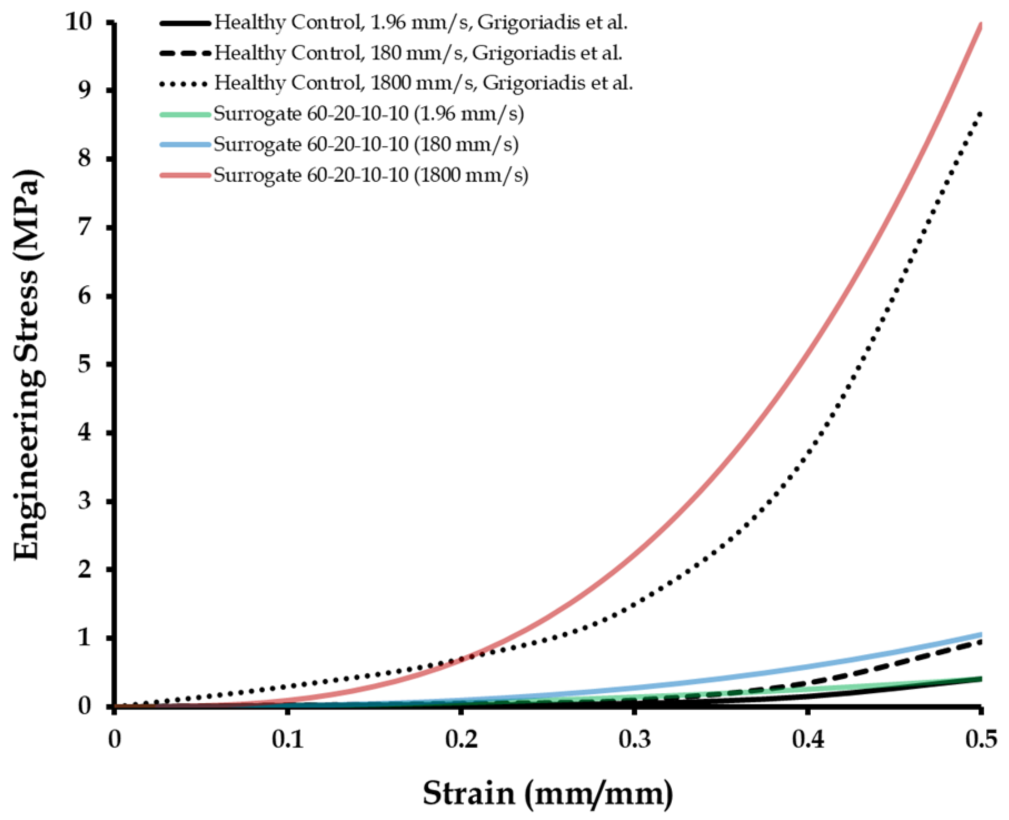
Arnab Chanda, and Stephen McClain. "**Mechanical Modeling of Healthy and Diseased Calcaneal Fat Pad Surrogates.**" Biomimetics 3.3 (2018): 27.

ARTIFICIAL NORMAL/DISEASED CALCANEAL FAT PAD

- **Cyclic and High Strain Rate Tests**
  - Compare with human fat pad tissue properties

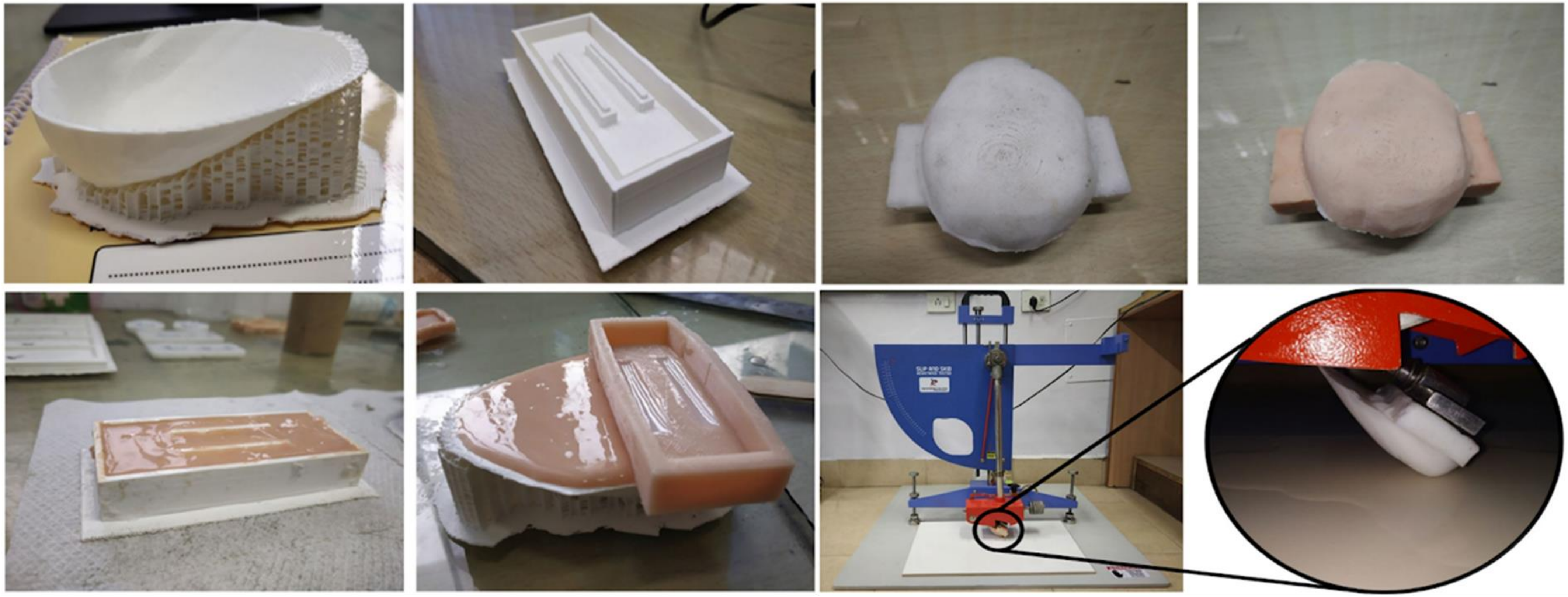


Cyclic loading of Fat Pad compared with surrogate



High strain rate loading of Fat Pad compared with surrogate

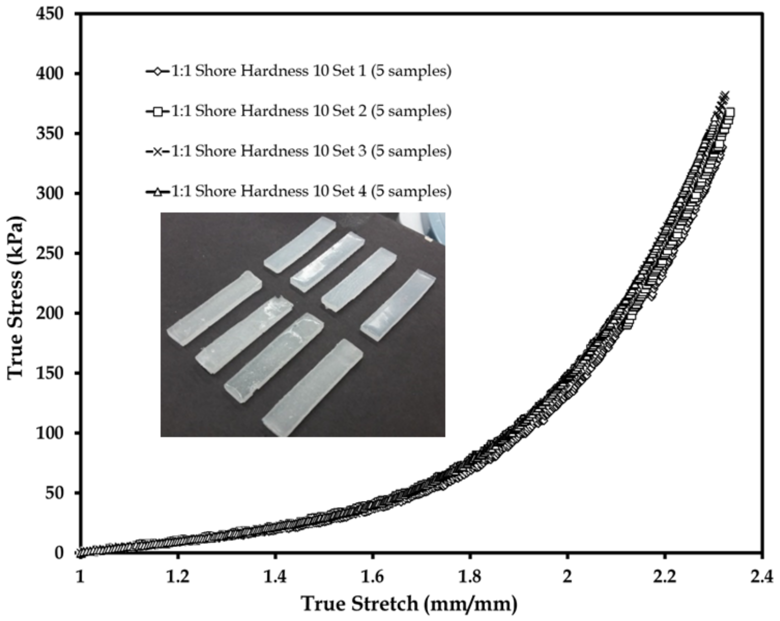
ARTIFICIAL HEEL SURROGATE-FRICTION TESTS



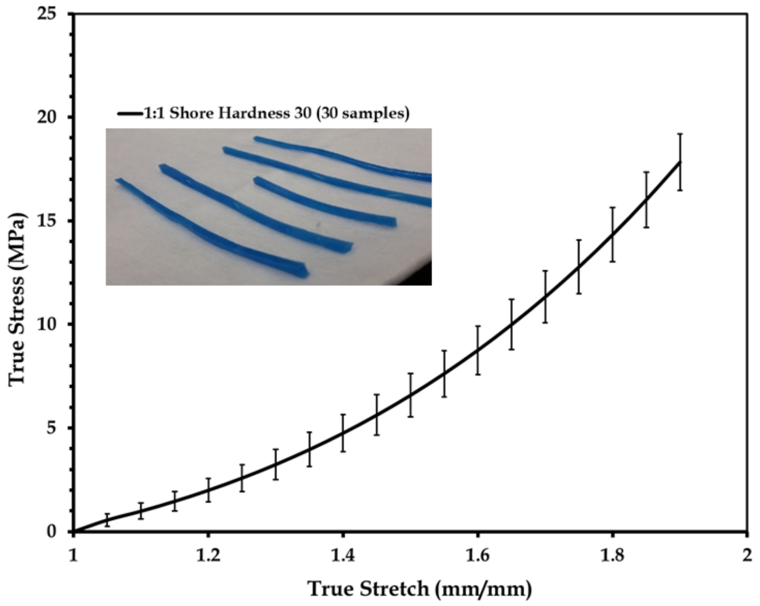
Testing of heel surrogate for various slips and falls conditions

ARTIFICIAL ANISOTROPIC TISSUE

- **Fabrication Methodology**
  - Soft Matrix (Two-Part Silicone)
  - Hard Fibers (Two-Part Silicone)
  - 20 test coupons generated
- **Mechanical Testing**
  - Specimen size: Length=50 mm, Width= 10 mm, Thickness=1-4 mm
  - Constant strain rate (0.4 mm/s)



Soft Matrix Material

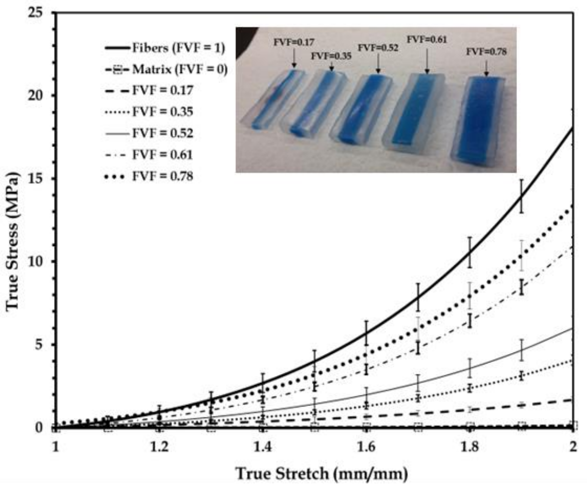


Hard Fiber Material

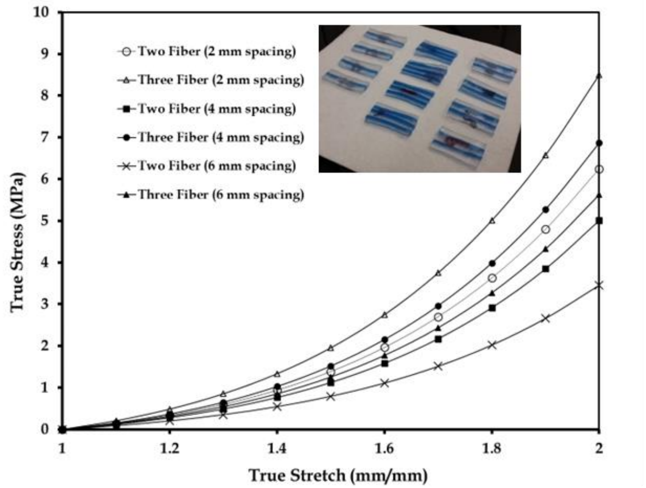
Chanda, Arnab, and Christian Callaway. "**Tissue Anisotropy Modeling Using Soft Composite Materials.**" Applied bionics and biomechanics 2018 (2018).

ARTIFICIAL ANISOTROPIC TISSUE

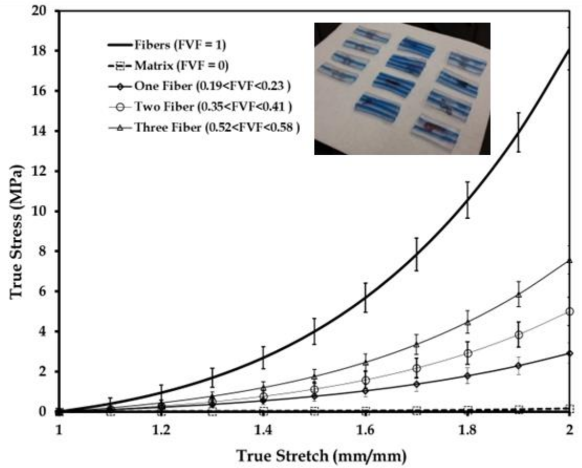
Composite stiffens with increasing FVF



Composite becomes complaint with increasing fiber spacing

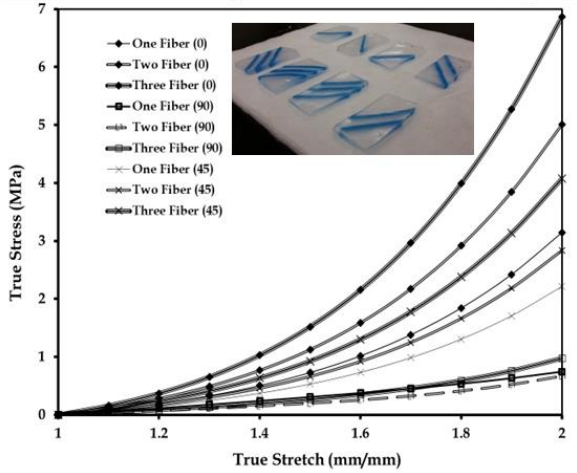


Composite stiffens with increasing number of fibers

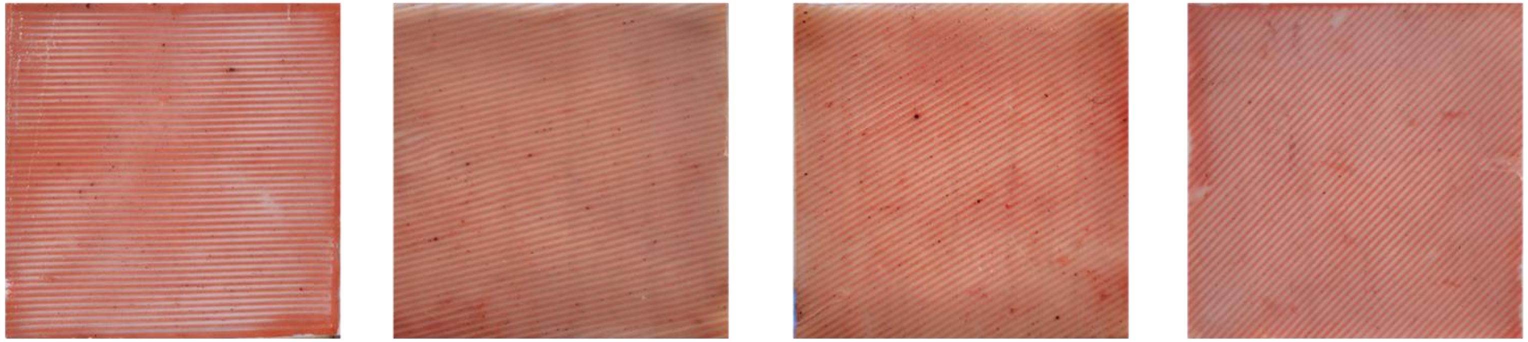


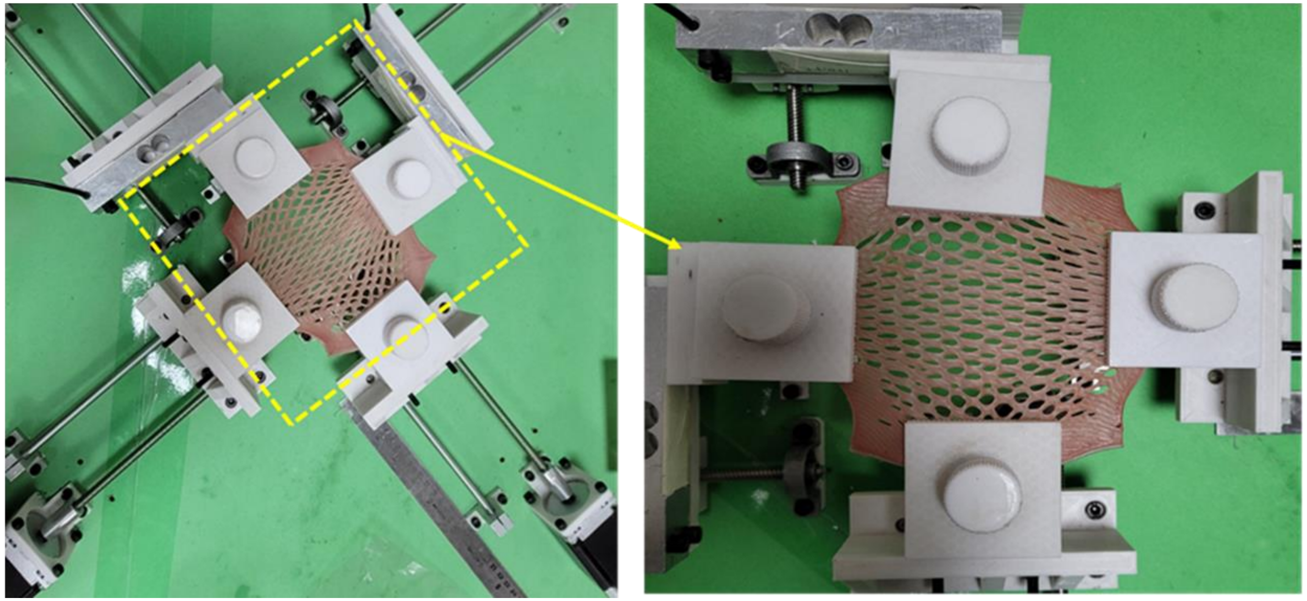
Chanda, Arnab, and Christian Callaway. "**Tissue Anisotropy Modeling Using Soft Composite Materials**." *Applied bionics and biomechanics* 2018 (2018).

Composite becomes complaint with increasing fiber angle



ADVANCED ARTIFICIAL ANISOTROPIC TISSUE



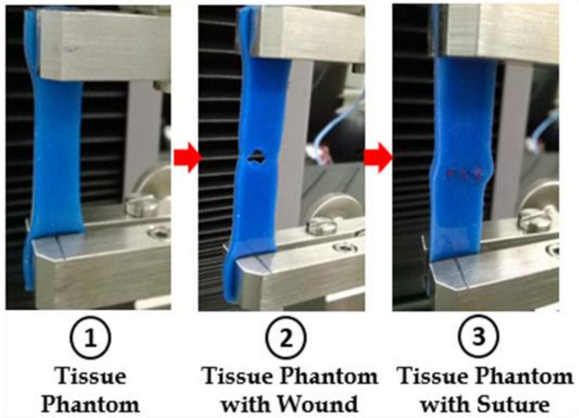


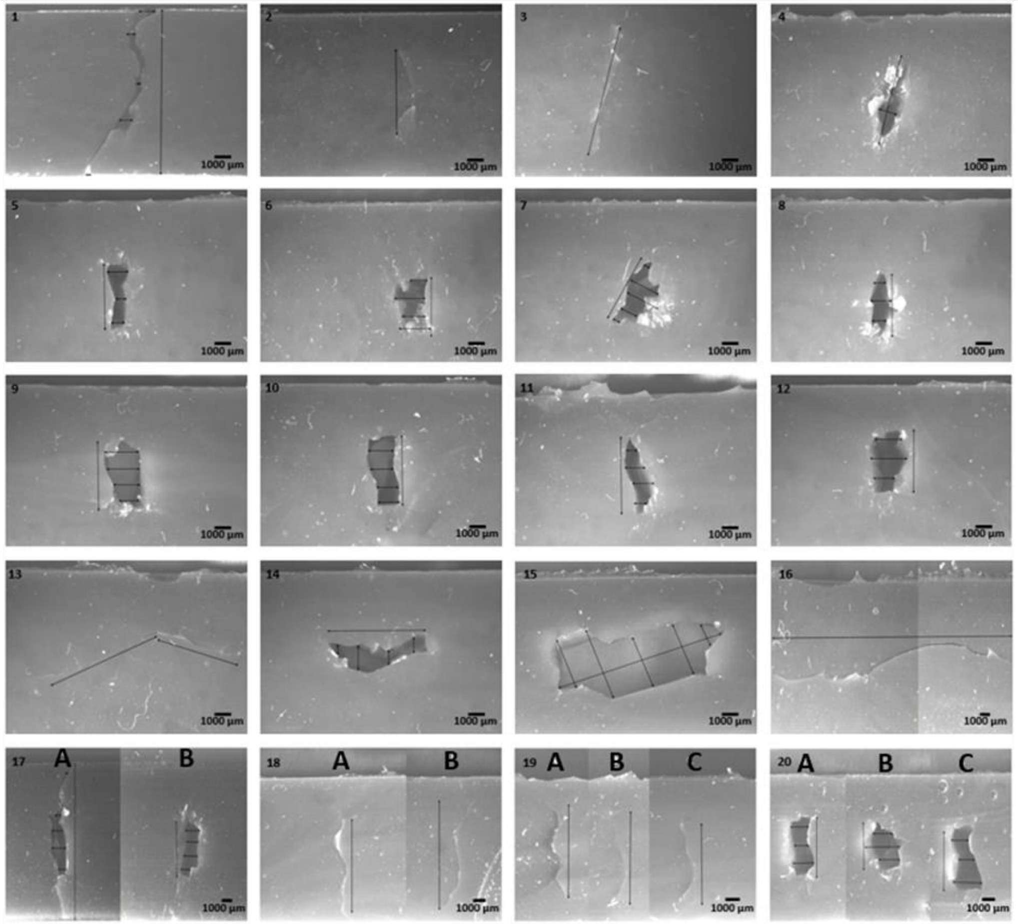
SURGICAL APPLICATIONS

SOFT TISSUE DAMAGE AND REPAIR

- Wound-Suture (*Global*)
  - **Artificial Human Skin**
  - **Different Wound Geometries**
    - Long/Short
    - Top/Center/Bottom
  - **Interrupted Sutures**
  - **Hyperelastic Relationships**

$$\sigma_{Veronda-Westmann} = 2(\lambda^2 - \frac{1}{\lambda})c_1c_2(e^{c_2(I_1-3)} - \frac{1}{2\lambda})$$

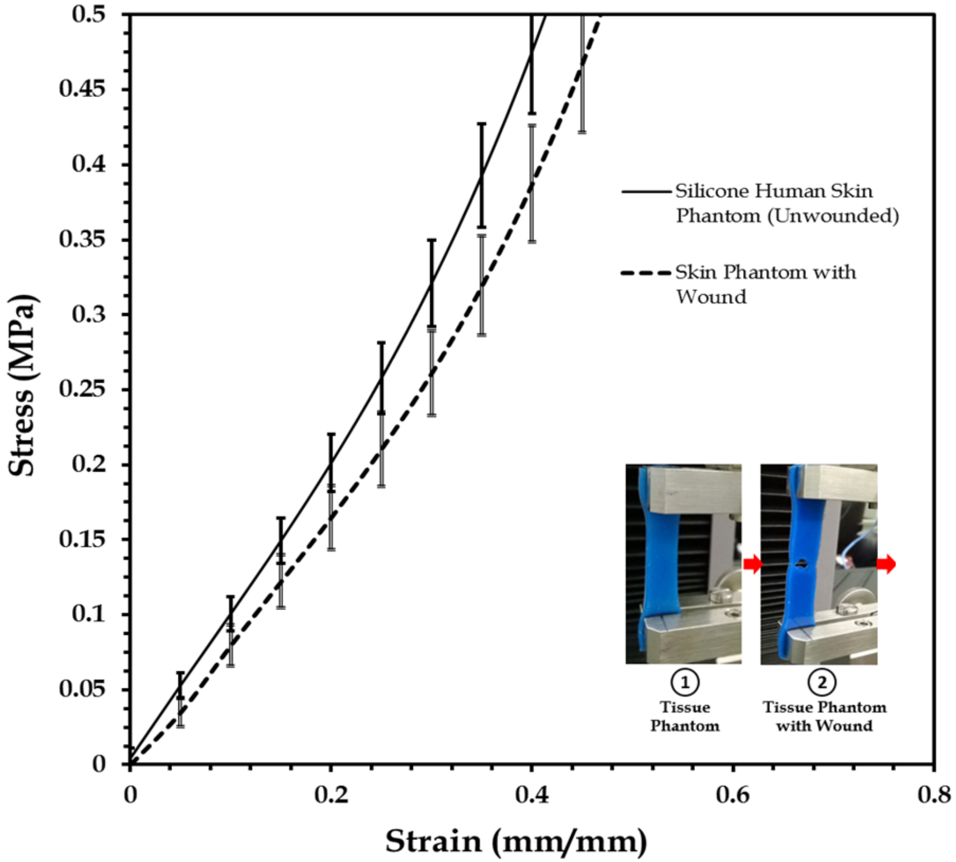




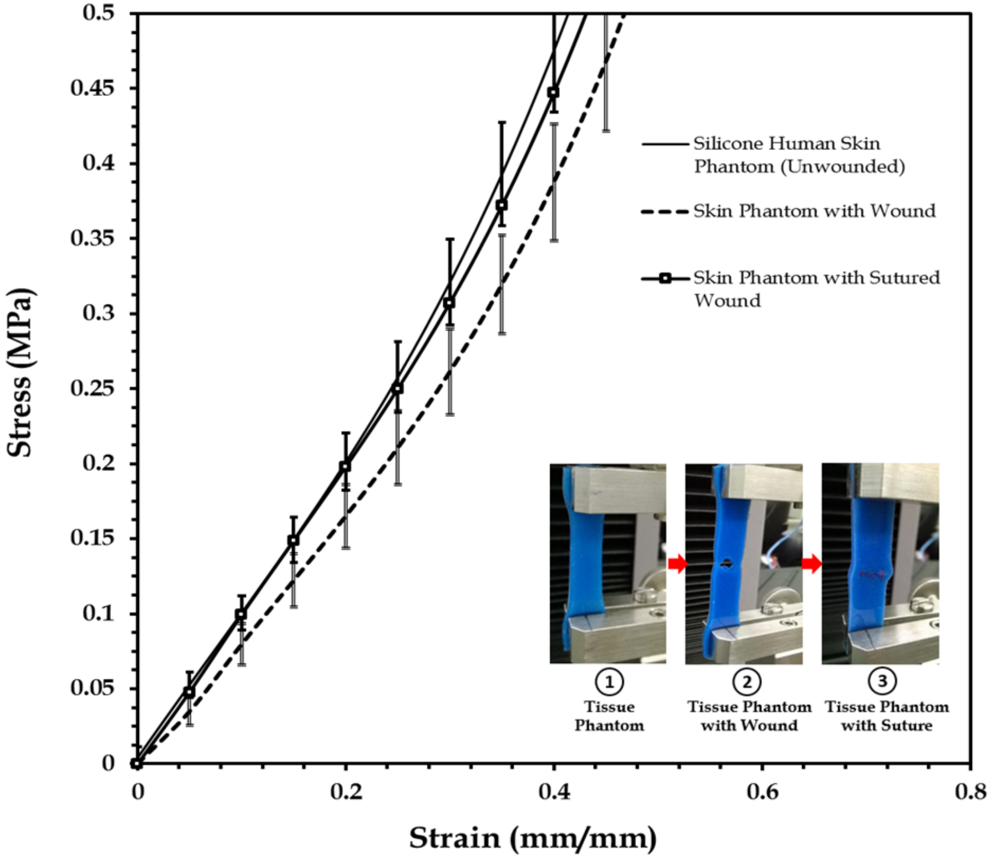
Wound Geometries

Chanda, Arnab, et al. **"Experimental study on tissue phantoms to understand the effect of injury and suturing on human skin mechanical properties."** *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine* 231.1 (2017): 80-91.

SOFT TISSUE DAMAGE AND REPAIR



Average Stress versus Strain Plots for Unwounded and Wounded Specimens



Average Stress versus Strain Plots for Unwounded, Wounded and Sutured Specimens

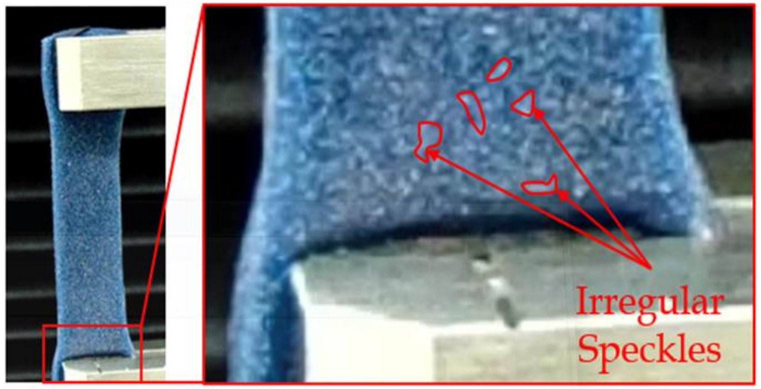
Chanda, Arnab, et al. **"Experimental study on tissue phantoms to understand the effect of injury and suturing on human skin mechanical properties."** *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine* 231.1 (2017): 80-91.

LOCAL DAMAGE STUDY-DIGITAL IMAGE CORRELATION (DIC)

- Wounds (*Local*)

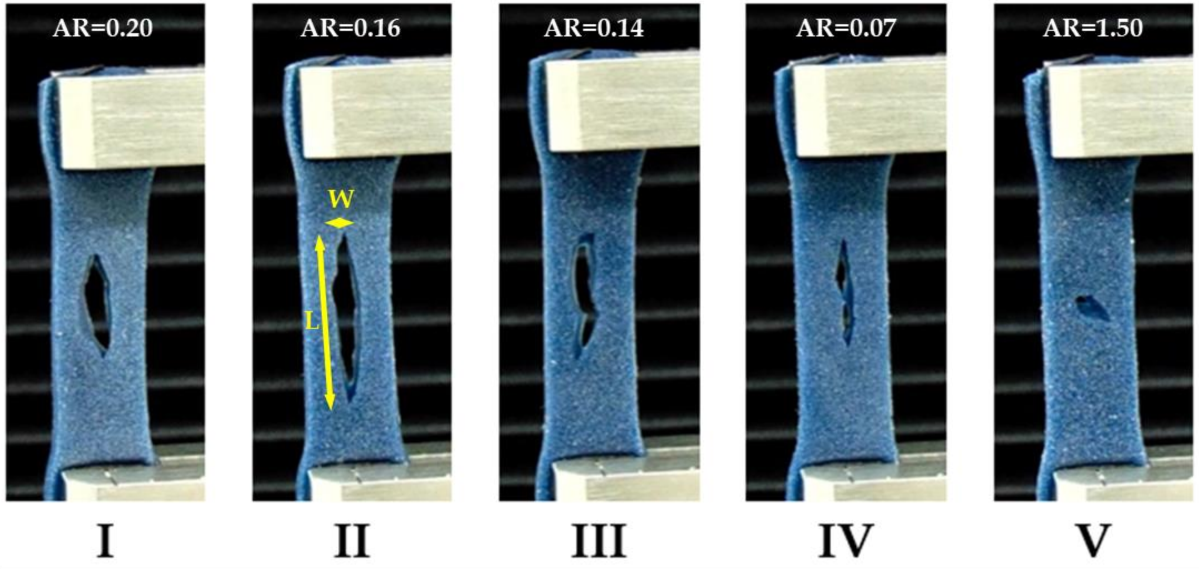
1. **Artificial Human Skin**
   - 10 test coupons
2. **Irregular Speckle Patterns**
3. **Video Imaging**
   - 20.1 Mega Pixel Sony DSC-H400 SLR camera

- **VIC 2D Image Correlation Software**
  - Length calibration
  - Image processing



Irregular Speckle Patterns used for DIC

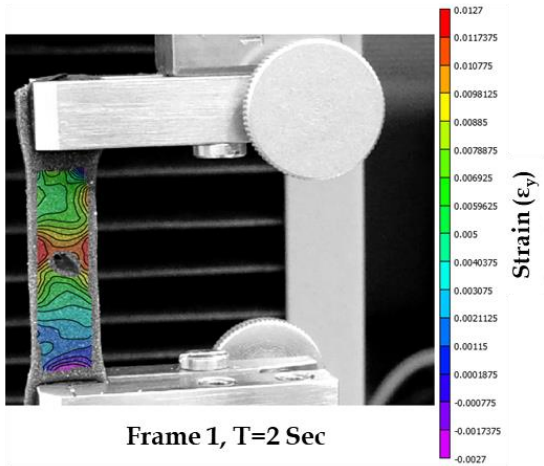
- **Different Wound Geometries**
  - Aspect ratios (AR=W/L) calculated



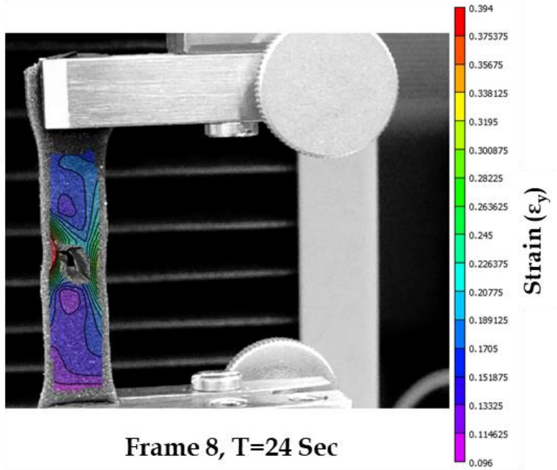
Human Skin Surrogates with Wounds

ASYMMETRIC SHORT WOUND-DIGITAL IMAGE CORRELATION (DIC)

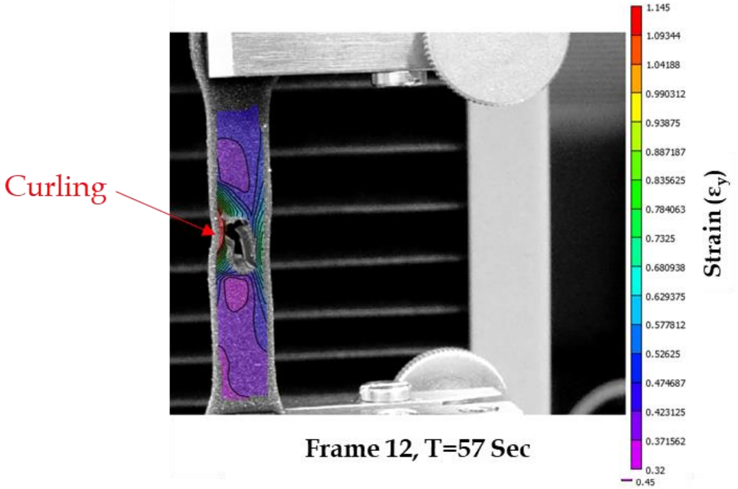
- Significant strain build-up on left of the wound



Frame 1, T=2 Sec

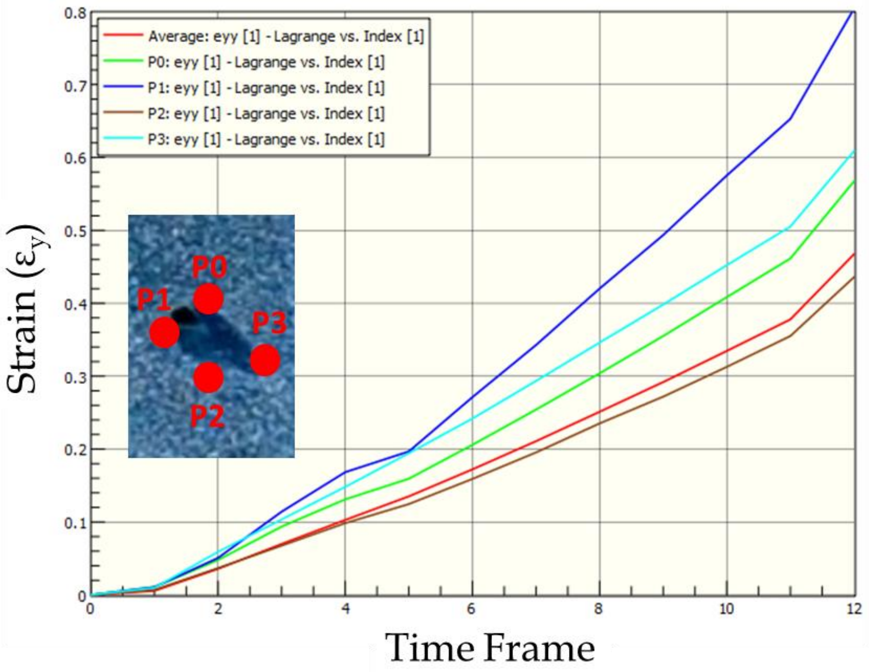


Frame 8, T=24 Sec



Frame 12, T=57 Sec

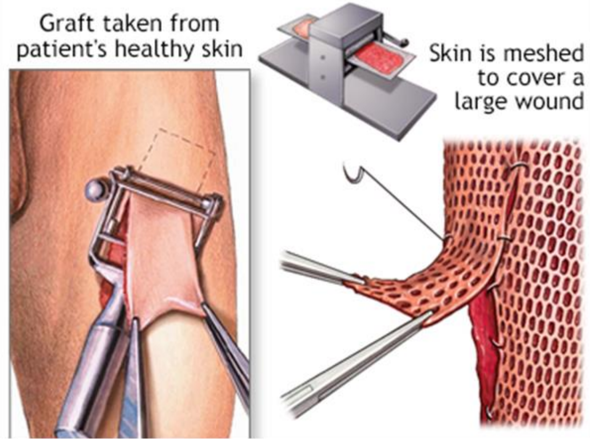
- 4 markers placed around wound
  - Strain build up around the wound shifted to left (P1)
  - Tearing was observed with time
  - Tissue curling was observed due to strain build-up and tearing on the left



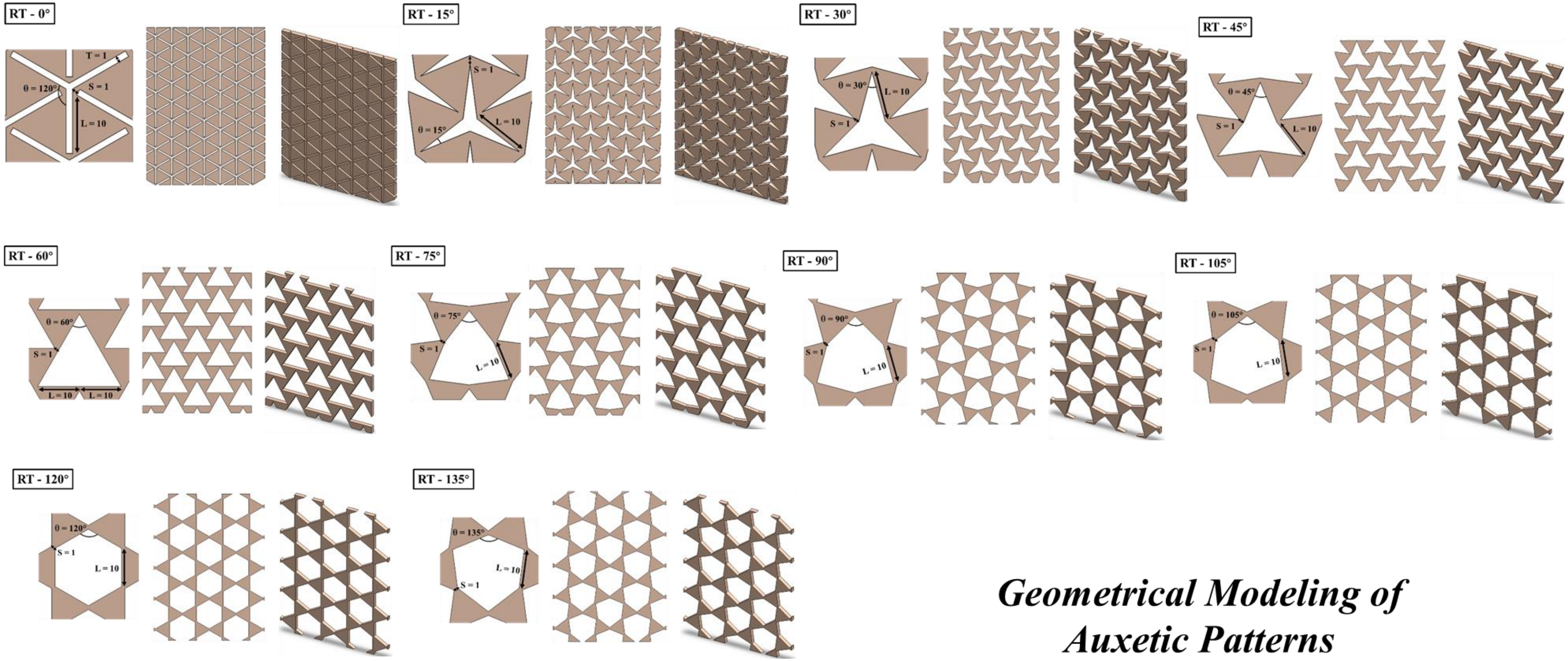
<u>Strains Tracked around Wound</u>

Testing of Artificial Skin Graft Simulants

- The expansion of the skin grafts plays a key role in treating severe burn injuries.
- In this work, the expansion potential of skin grafts with novel rotating triangle (RT) shaped auxetic incision patterns were investigated extensively.
- A skin simulant was employed and a range of RT configurations, with internal angles varying from 0° to 135°, were tested through the development of skin graft simulants.
- Mechanical testing and digital image correlation (DIC) were used to characterize the Poisson's effect, meshing ratios, and induced stresses of the skin graft simulants.
- Such experimental findings on expansion potentials and estimations of mechanical properties with auxetic skin grafts simulants have not been reported to date and would be indispensable for further research in skin graft expansion and severe burn injury treatment.



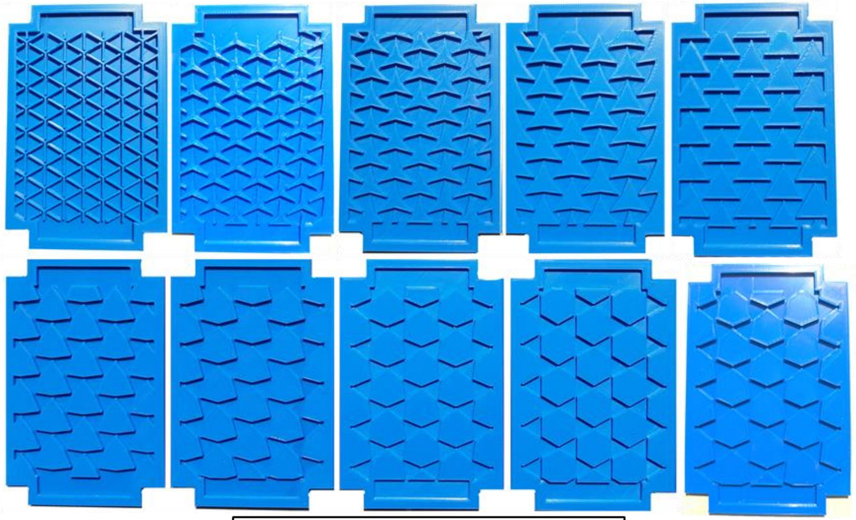
Testing of Artificial Skin Graft Simulants



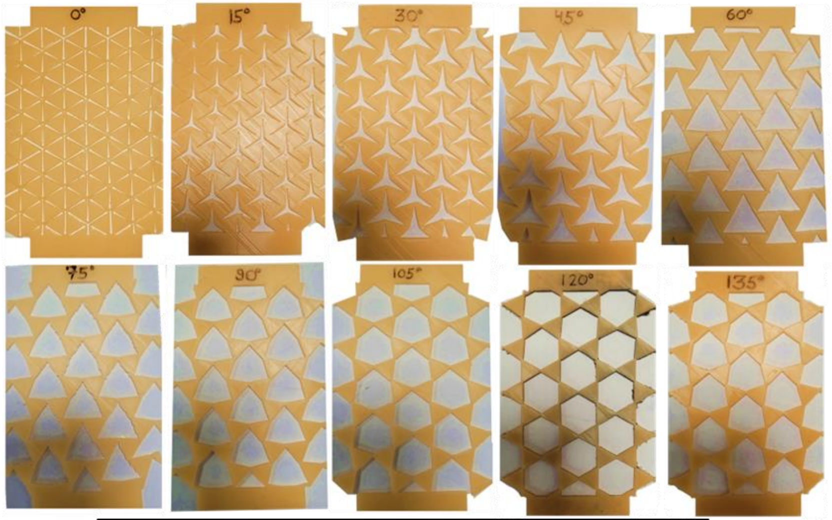
Unit cell and RT skin graft models with internal angle ranging from 0° to 135°

Geometrical Modeling of Auxetic Patterns

Testing of Artificial Skin Graft Simulants



3D printed skin grafts molds

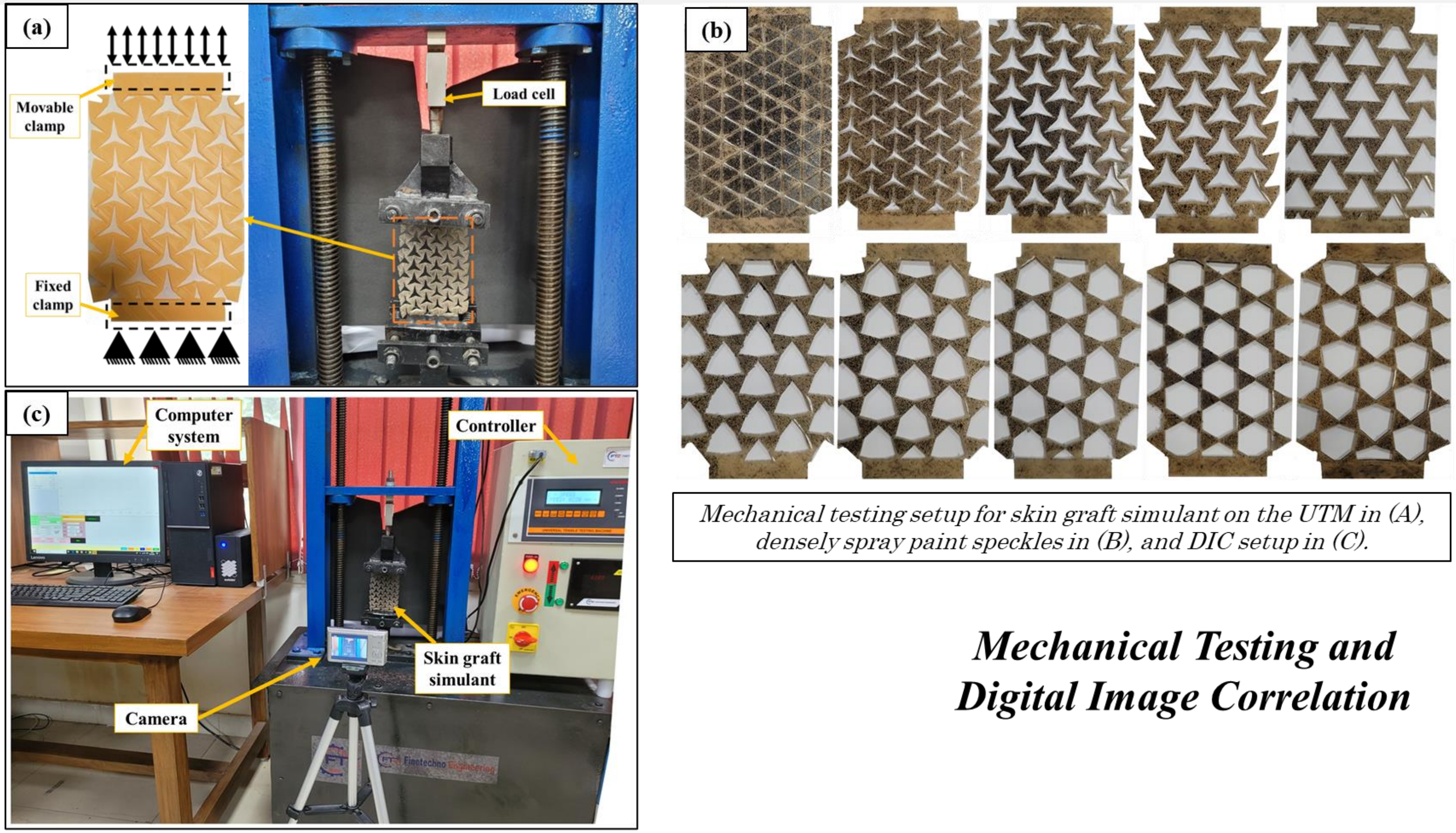


Skin grafts simulants with varying RT angles

- The geometrical auxetic models were used to develop negative graft molds with a constant dimension of 100 mm × 75 mm × 2.5 mm.
- A Voxelab Aquila 3D printer was used to 3D print the STL models of the auxetic graft molds with PLA (Polylactic Acid) material.
- These 3D printed molds were employed further to cast the skin graft simulants.

Development of Skin Graft Simulants

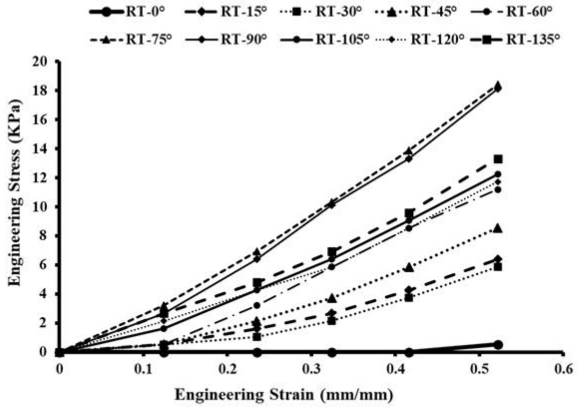
Testing of Artificial Skin Graft Simulants



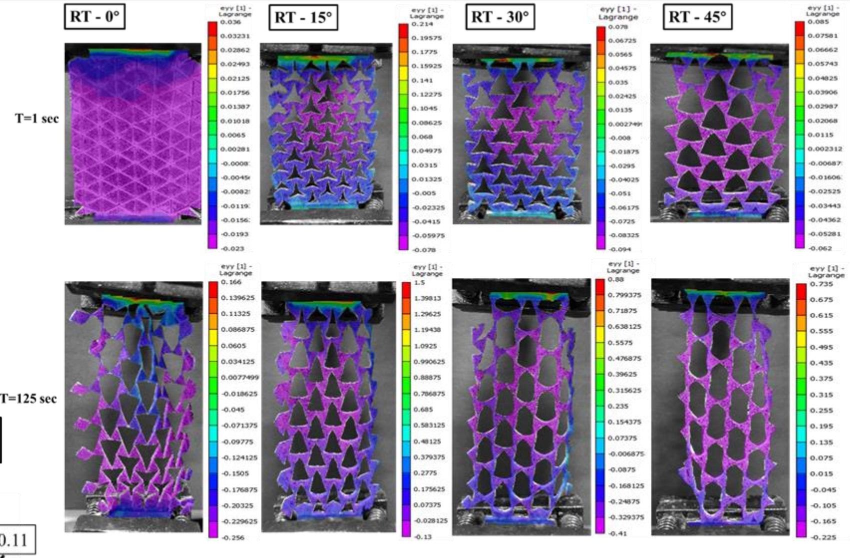
Mechanical testing setup for skin graft simulant on the UTM in (A), densely spray paint speckles in (B), and DIC setup in (C).

Mechanical Testing and Digital Image Correlation

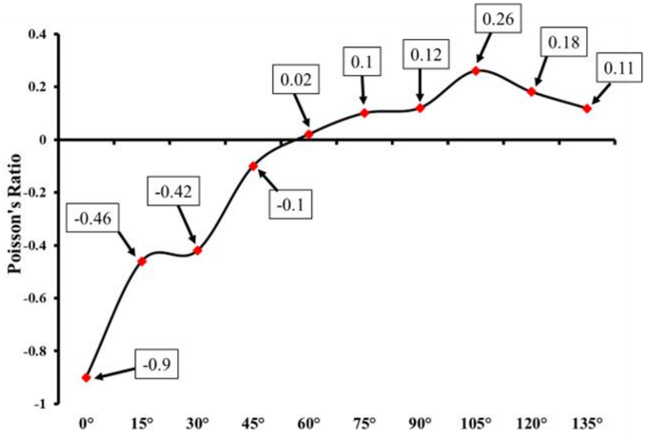
Testing of Artificial Skin Graft Simulants



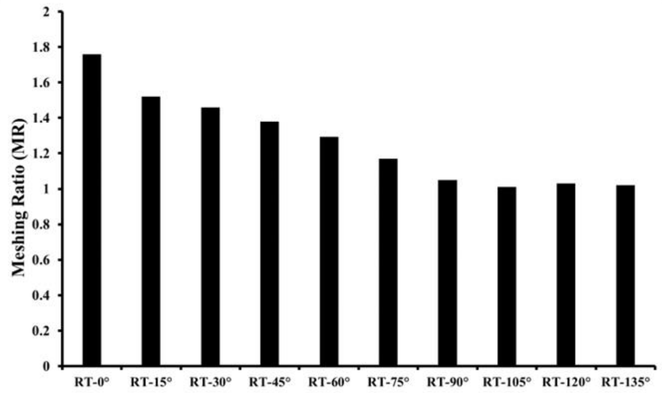
Stress-strain plot of skin graft simulant models



Strain distribution observed through DIC in skin graft simulants (Representative 0°-45°)



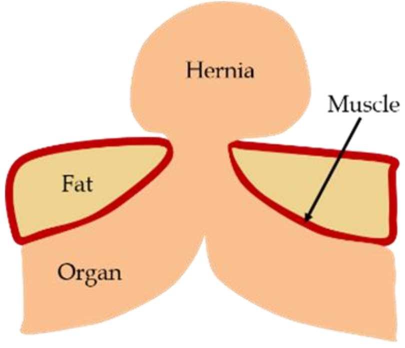
Poisson's ratio of RT skin graft simulants at 50% strain



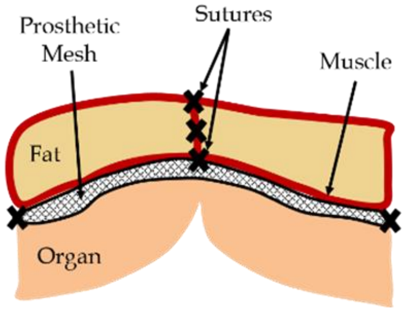
Uniaxial Meshing ratios for RT skin graft simulants

Hernia Mesh Testing

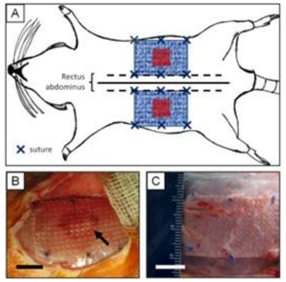
- Background
  - **20,000,000 hernia repair surgeries per year** [1]
  - **Hernia surgery with prosthetic meshes cause:**
    - *Pain and Infection (Biological Issue)*
    - *Hernia recurrence (Loading Issue)*
    - *Mesh contraction (Loading Issue)*
    - *Mesh failures (Loading Issue)*
  - **Literature (Studies to date):**
    - *Mesh Biocompatibility (Animal Models)*
    - *Dry and Wet Mechanical Tests*
  - **Literature Gap:**
    - *Lack of mesh and human tissue interaction tests*
    - ***Reason:** Lack of human tissues*



Hernia

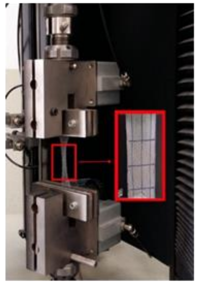


Hernia Repair-Mesh



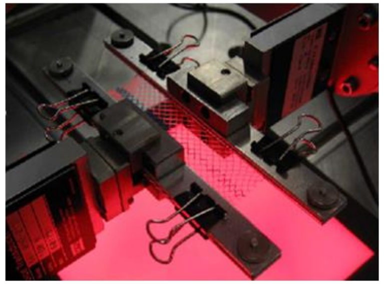
Animal Tests

Wolf, Matthew T., et al. "Polypropylene surgical mesh coated with extracellular matrix mitigates the host foreign body response." *Journal of Biomedical Materials Research Part A: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials* 102.1 (2014): 234-246.



Uniaxial Test

Todros, Silvia, et al. "Investigation of the Mechanical Behavior of Polyester Meshes for Abdominal Surgery: A Preliminary Study." *Journal of Medical and Biological Engineering* (2017): 1-12.



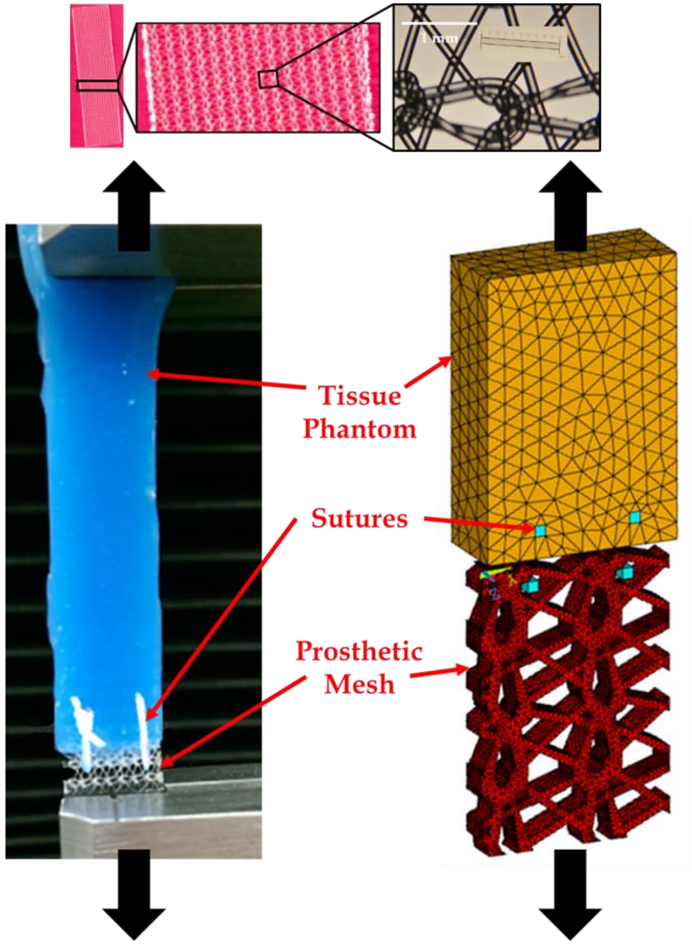
Bi-axial Test

Röhrnbauer, B., and Edoardo Mazza. "Uniaxial and biaxial mechanical characterization of a prosthetic mesh at different length scales." *Journal of the mechanical behavior of biomedical materials* 29 (2014): 7-19.

Hernia Mesh Testing

- ## Research Work
  - **Mesh-Tissue-Suture Experimental Model**
    - *Fabricate pelvic tissue surrogate (phantom)*
    - *Suture prosthetic mesh with tissue surrogate*
  - **Mesh-Tissue-Suture Computational Model**
    - *Microscopic prosthetic mesh imaging and repeating unit identification*
    - *Development of geometric model of prosthetic mesh (PROLENE)*
    - *Computationally suture mesh and tissue*

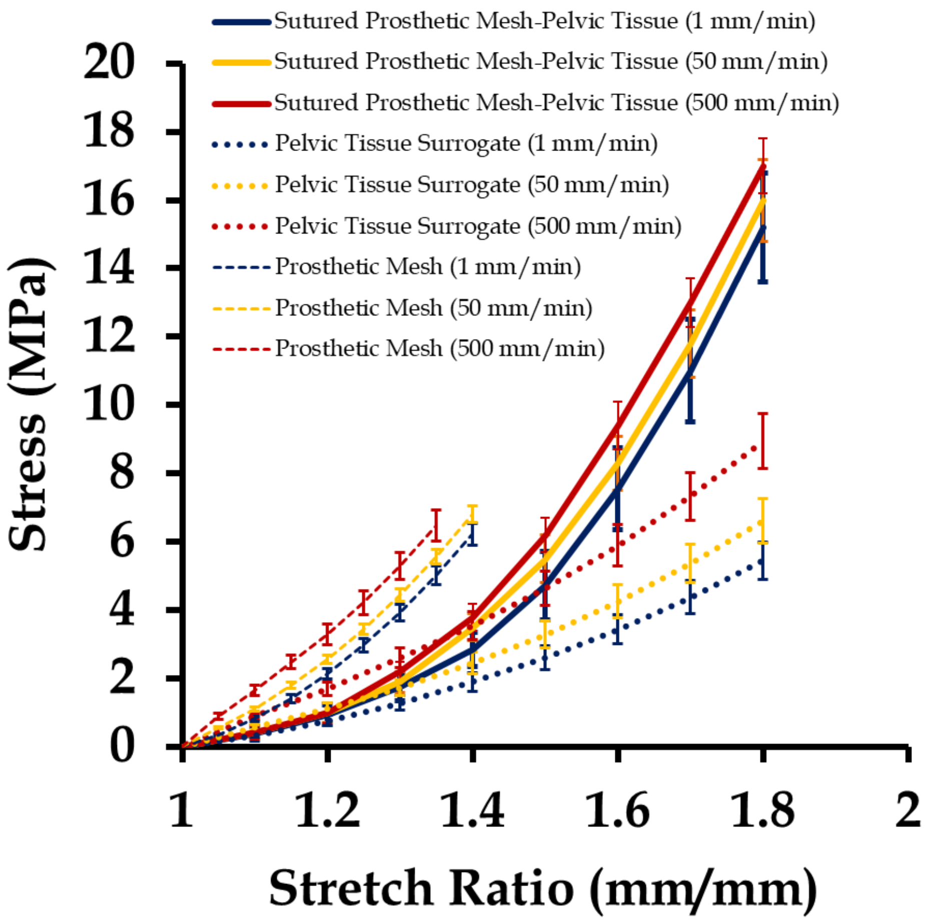
  - **<u>Mechanical Testing:</u>**
    - *Strain Rates: 1, 50, and 500 mm/min*
    - *Individual component tests*
    - *Mesh-Tissue-Suture tests*



Chanda, Arnab, Tysum Ruchti, and Weston Upchurch. **"Biomechanical Modeling of Prosthetic Mesh and Human Tissue Surrogate Interaction."** Biomimetics 3.3 (2018): 27.

Hernia Mesh Testing

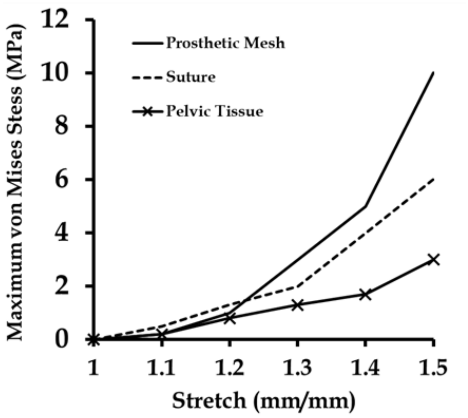
- ## Test Results
  - **Experimental Testing**
    - *Global mechanical properties identified*
    - *For stretch<1.5, tissue is the major load bearing component*
    - *For stretch>1.5, the prosthetic mesh underwent permanent deformation*
    - *Prosthetic mesh twisting observed about loading axis*
    - *Minimal effect of strain rates-indicating prosthetic mesh as dominant load bearing component*



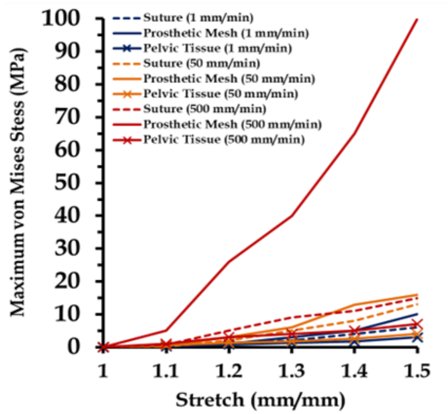
Chanda, Arnab, Tysum Ruchti, and Weston Upchurch. **"Biomechanical Modeling of Prosthetic Mesh and Human Tissue Surrogate Interaction."** Biomimetics 3.3 (2018): 27.

Hernia Mesh Testing

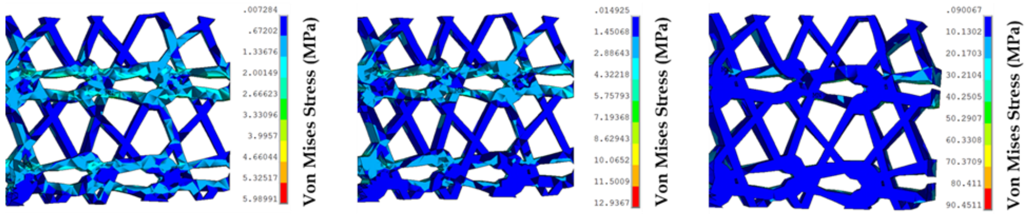
- ## Test Results
  - **Computational Model**
    - *Maximum stress on prosthetic mesh at location of sutures*
    - *At stretch=1.5, maximum stress on prosthetic mesh approximately twice of average stress observed in experiments*
    - *Significant stress concentration in curved strands of prosthetic mesh*
    - *Tissue was the least stressed component*
    - *Very high stress (~90 MPa) on prosthetic mesh strands at high strain rates (500 mm/min)*
    - *Structural repeating unit of prosthetic mesh influences stress distribution*



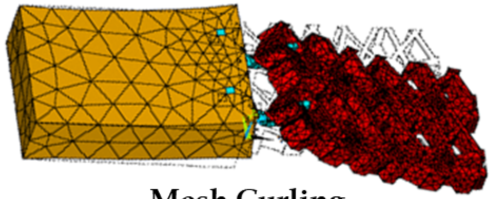
Quasi-Static Test



Strain Rate Tests



Strain Rate = 1 mm/min   Strain Rate = 50 mm/min   Strain Rate = 500 mm/min



Mesh Curling

BALLISTIC TESTING

Ballistic Tissue Simulants

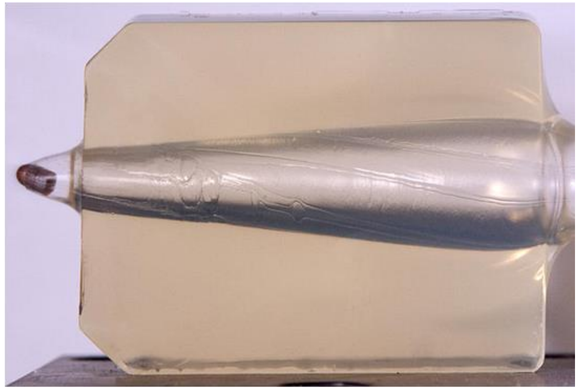
1. Ballistic interactions with the human tissues can cause irreparable injuries and death.

2. In combat, 20% of penetrating injuries occur to the head and its wounding account for 50% of combat deaths. Therefore, it is imperative to study the effect of ballistic loads in the head-neck region.

3. For both ethical and practical reasons, accurate tissue simulant materials are essential for ballistic testing, over cadavers and animal models.

4. A wide variety of different materials have been previously adopted for such roles, ranging from gelatin to ballistics soap. They are inaccurate in modeling soft tissue properties in high strain rate

5. To overcome this gap, development of an anatomically accurate tissue simulant based framework is proposed for low-velocity and high-velocity ballistic evaluation. The model will initially be validated in a skin-skull-brain model and extended to other tissues and organs.



Ballistic Tissue Simulants

State-of-the-Art of Ballistic Tissue Simulants

1. Cadavers

- *Organs and tissues from fresh and un-embalmed human cadavers have been used.*
- *The findings ranged from no effect on biomechanical properties, to decrease in tensile strength, and increase in tensile strength and elastic modulus.*
- *Human cadavers for ballistic research could generate biosafety, handling, and ethical issues.*

2. Animal models

- *Live and deceased animals including horses, cattle, goats, sheep, dogs and pigs have been used extensively to conduct trauma studies*
- *The use of pigs as a substitute for human tissue is a common scientific practice. However, the skin and subcutaneous tissue of pigs are thicker than humans*
- *The use of live large animals in ballistics testing or even other scientific research may cause ethical and moral issues*

Ballistic Tissue Simulants

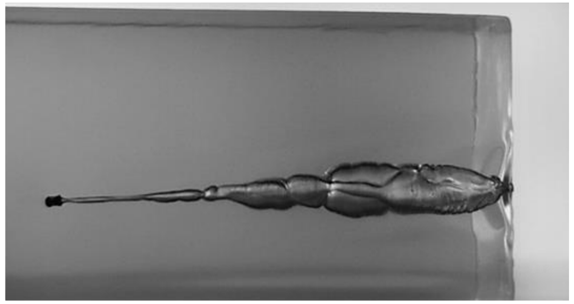
State-of-the-art of Ballistic Tissue Simulants

3. Ballistic ordnance gelatine (10% and 20%)

- *Ordnance gelatine is derived from collagen proteins in animal products.*
- *The strength and stiffness is not solely determined by the Bloom Number, but also the concentration and temperature during preparation.*
- ***Calibration of the gelatine was carried out using a small number of samples of porcine (thigh)**, thus a disagreement exists in relation to the results.*
- *It allows the visualisation and photographic representation of the projectiles. However, it lacks the bio-mechanical properties of most tissues. Also, bullet penetration behaviour is different from tissues.*

4. Synthetic tissue simulants: Soap, wet packs, and clay

- *Preferred over biological tissues as there are no ethical or biosafety issues*
- *These new synthetic simulants are non-elastic and the findings in these simulants cannot describe the wounding occurring in the human body*



Ballistic Tissue Simulants

Ballistic Head Simulants

1. Brain Simulants

- *No animal has a skull structure sufficiently similar to the human.*
- *Currently, many forensic investigators are using ten per cent gelatin as a simulant for brain tissue.*
- *Lazarjan et al. showed this by using a slow motion camera capturing a 5.5 mm caliber air rifle pellet fired into 3% and 5% gelatin and compared to fresh bovine brain. Their research concluded that gelatin is much more elastic than brain and, deforms and damages in a different manner*
- *No statistical difference was seen when the 10% gelatine was compared with 3, 5 and 7% gelatine and Permagel*

2. Skull Simulants

- *Literature describing ballistic rate impacts on animal skulls with or without a simulated brain is sparse, due to ethical and moral issues*
- *Some early work by Watkins et al. described using dried Asiatic skulls filled with 20 % gelatine. Heads were tested using 6.35 mm diameter ball bearings of mass 1.045 g at 370 m/s, 750 m/s, and 1,000 m/s*

Ballistic Tissue Simulants

Ballistic Skin Simulants

3. Skin Simulants

- *Structural layers of human skin have different properties and absorb varying amounts of impact energy which changes with location on the body and a person's age.* ***No simulant is available to date***
- *An impacting bullet makes the skin to stretch, partially crush and finally rupture, allowing the bullet to enter sub-cutaneous tissue. For a suitable ballistic skin simulant, the threshold velocity v_{th} required by a given projectile for penetration is important.*
- *As per law enforcement perspective, the reference person has been defined to be a 30-year-old male with target skin at anterior thorax.*
- *A good tissue simulant must have similar deceleration of the projectile; deformation behaviour of the projectile; kinetic energy dissipation; temporary cavity formation; and permanent cavity diameter; and reproducibility. Therefore, the simulant does not need to possess exactly the same biomechanical properties as living tissue as long as the results can be measured and appropriately extrapolated or scaled.*

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(12) **United States Patent**
Chanda et al.

(10) **Patent No.: US 10,049,601 B2**
(45) **Date of Patent: Aug. 14, 2018**

(54) **BIOFIDELIC SKIN SIMULANT**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/204,353**

(22) Filed: **Jul. 7, 2016**

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,481,001 A *	11/1984	Graham	G09B 23/285 434/267
5,312,755 A	5/1994	Madsen et al.	
6,136,039 A *	10/2000	Kristinsson	A61F 2/7812 623/36
7,222,525 B1	5/2007	Jones	
8,215,165 B2	7/2012	Giurintano et al.	
9,123,261 B2 *	9/2015	Lowe	G09B 23/30
2007/0116766 A1	5/2007	Amick	
2010/0167254 A1 *	7/2010	Nguyen	G09B 23/30 434/272
2011/0207104 A1 *	8/2011	Trotta	B29C 39/006 434/267

(Continued)

FOREIGN PATENT DOCUMENTS

WO 20130171444 A1 7/2013

OTHER PUBLICATIONS

HIGHLIGHTS

- Ethical and biosafety issues associated with cadaveric and live human tests
- **Need for realistic and low-cost artificial tissues for surgical training and ballistic testing**
- Most researched Artificial Skin (synthetic and hydrogel based)
- Artificial Artery, Brain, Fat tissues were discussed
- Artificial anisotropic tissues were discussed
- **Surgical Applications** were discussed
  - Wound-Suture research
  - Skin Grafing
  - Hernia mesh testing
- **Ballistic Applications** were discussed