# Enhanced Mechanical Characteristics of PET/PU Electrospun Vascular Grafts with Additive Manufacturing Reinforcement for Vascular Graft Applications


Jordan Zimmerman[1], Kiran R. Adhikari[2], Vinoy Thomas[3]

[1] Department of Chemical, Biological, and Materials Engineering, University of Oklahoma [2] Department of Physics, University of Alabama at Birmingham
[3] Department of Materials Science and Engineering, University of Alabama at Birmingham


## INTRODUCTION

Each year, cardiovascular diseases cause over 600,000 deaths in the United States alone, with peripheral arterial disease (PAD) being a common type [1]. PAD requires long grafts with small diameters for replacement, though the failure rate is high due to low patency. Most notably, current synthetic grafts can kink or loop over long distances, occluding blood flow [2,3].

To address these issues, this project combined, in a novel fashion, two processes that have recently garnered considerable attention in tissue engineering: electrospinning and 3D printing. Electrospinning is a facile fiber deposition technique draws fibers from polymer solution onto a surface, with aggregated fibers having high porosity, tunability, and biocompatibility [4]. 3D printing, or additive manufacturing, extrudes melted polymers in different patterns to fabricate customizable tissue scaffolds exhibiting favorable biomechanical properties [5]. Two polymers were used for electrospinning of grafts: PU, a green elastomer suitable for the body's pulsatile environment, and PET, a polymer widely used in vascular graft replacements.

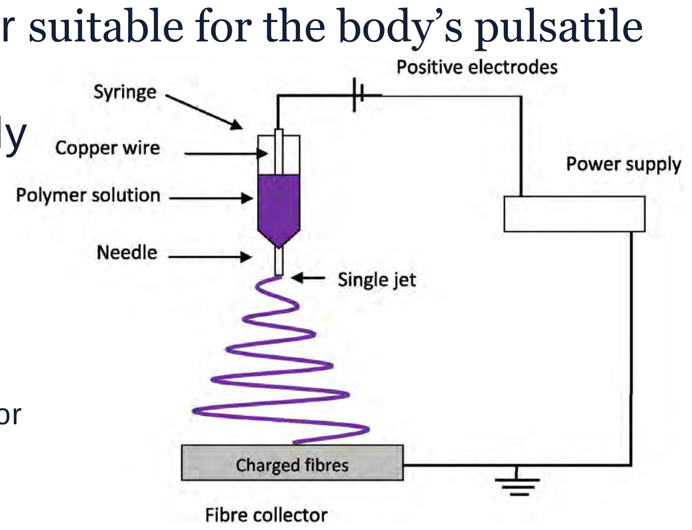



Figure 1 [6]:
Diagram of electrospinning. Voltage differential causes Taylor cone to form, from which fibers deposit onto grounded surface.

## MATERIALS AND METHODS

A polymer blend of polyethylene terephthalate (PET) and polyurethane (PU) in 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP) was spun. The PET/PU solute (4:1 ratio) comprised 18% of the solution by weight.

Polylactic acid (PLA) or polyethylene terephthalate glycol (PETG) were subsequently extruded onto the graft. The extruder head moved laterally at a constant speed along the graft during extrusion while a collector rotated at different rotational speeds (50, 100, 150 and 200 RPM), yielding samples with varied mechanical properties.

To evaluate mechanical properties, samples were tested according to their tensile strength in the axial and radial directions using a DMA machine as well as according to their kink radii.

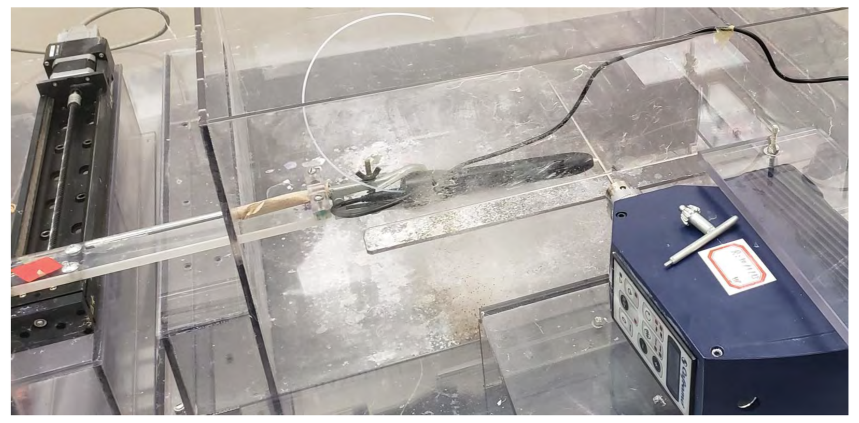


Figure 2:
Extruder head mounted in electrospinning apparatus. Lower right: drill to spin mandrels. Left: motor and screw to facilitate lateral motion of extruder head or needle.

## RESULTS AND DISCUSSION

### DMA Tensile – Longitudinal Direction

Tensile properties were evaluated with a modified setup for a DMA analyzer. Apparent elastic modulus (AEM), in MPa, was calculated by measuring the slope of the elastic region on the stress-strain curve.

Results indicate that AEM in the longitudinal direction increases for larger RPM values of modified grafts. PETG-modified grafts have larger moduli as compared to PLA-modified grafts when holding RPM constant. The control grafts' AEM suggest that reinforcement by way of additive manufacturing leads to little or no improvement in the longitudinal direction.

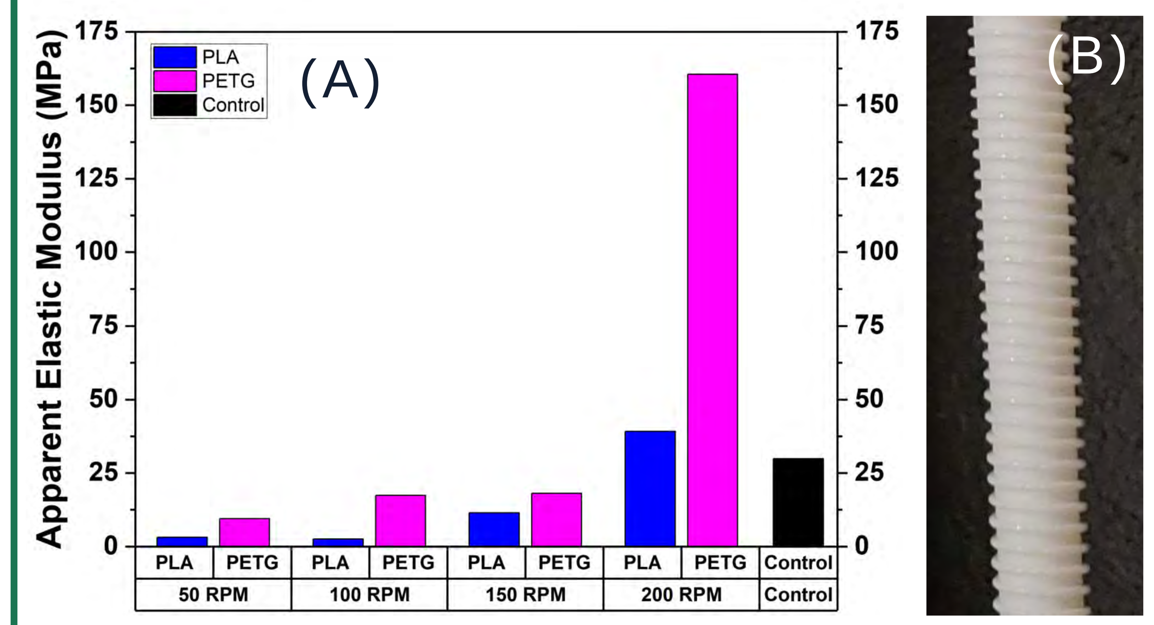
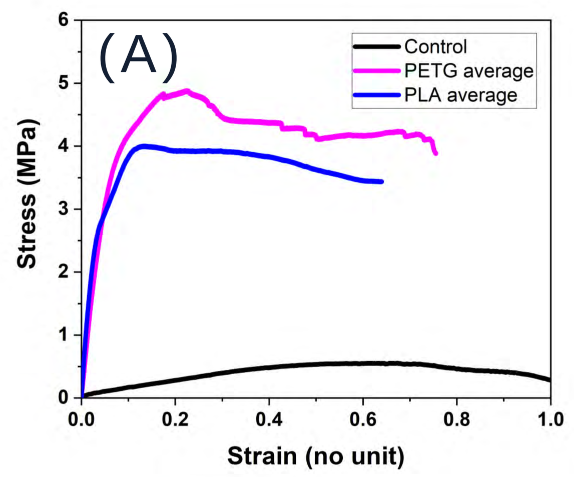



Figure 3:
(A) Apparent elastic moduli in longitudinal direction of grafts, sorted by RPM during extrusion; (B) Image of PLA-reinforced graft at 50 RPM

### DMA Tensile – Radial Direction

Tensile testing and elastic modulus were carried out and calculated as described above. Results indicate that elastic modulus in the radial direction is substantially higher than that of control grafts. Although PLA-reinforced grafts do not display an apparent trend, the trend of larger moduli for higher RPM (illustrated above) holds among PETG-reinforced grafts. Regardless, averages of strain-stress curves illustrate the significant improvement of reinforced grafts in the radial direction, suggesting a tangible improvement by way of additive manufacturing.



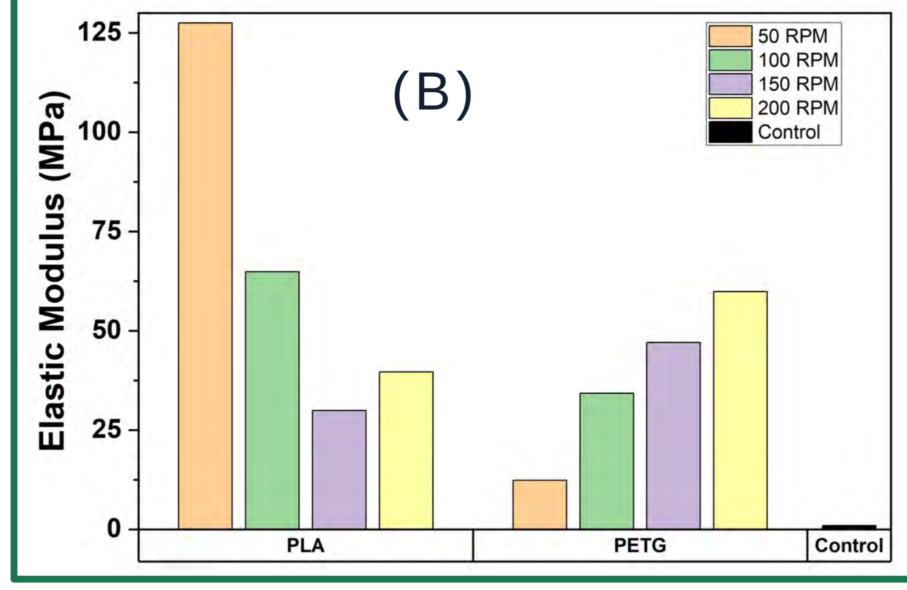




Figure 4:
(A) Summary of radial strain vs. stress for each material/ reinforcement; (B) Elastic moduli in radial direction for control and reinforced grafts, sorted by material

## RESULTS AND DISCUSSION

### SEM and DiameterJ

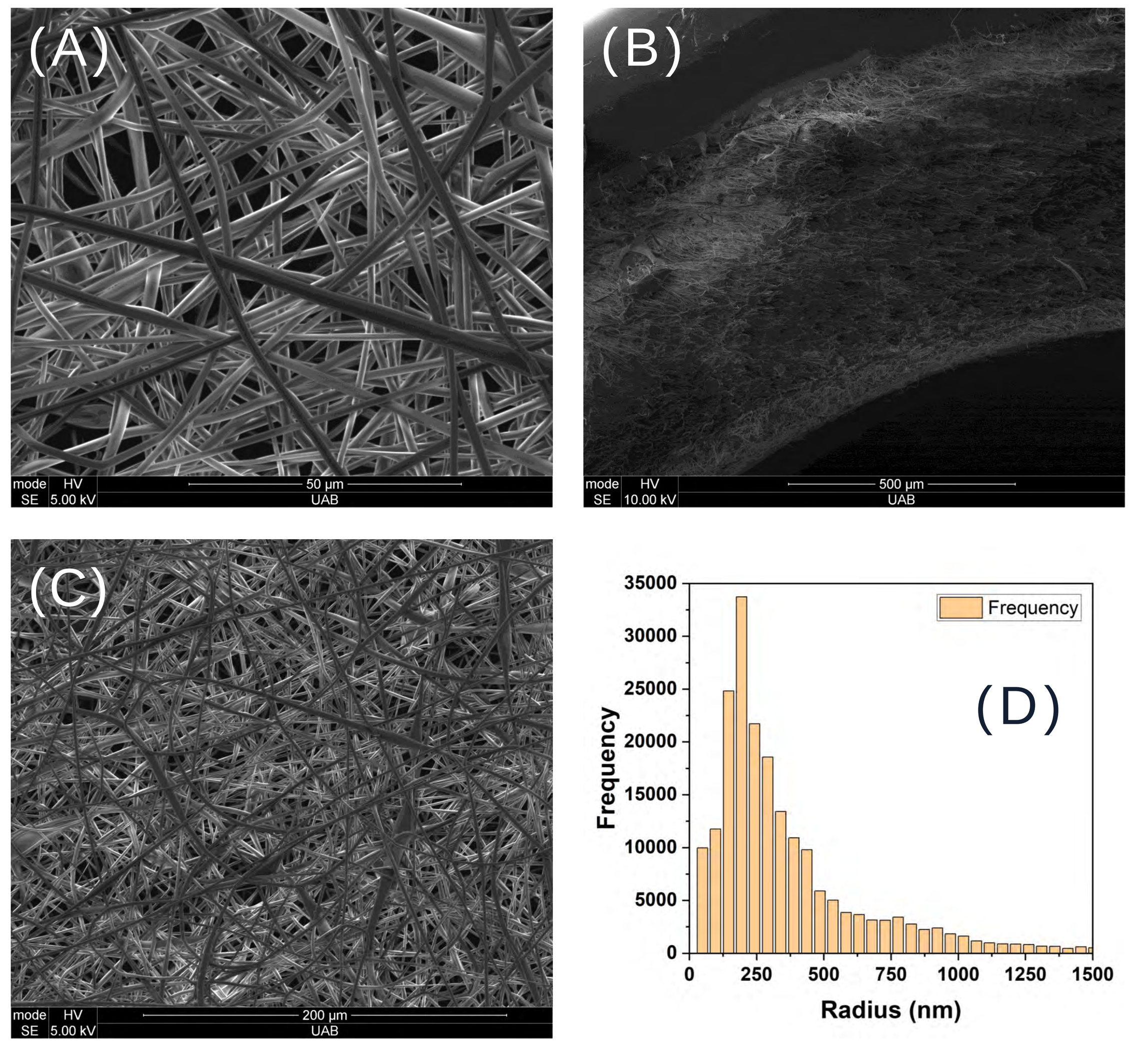



Figure 5:
(A) SEM image of PET/PU fibers; (B) SEM cross-sectional image depicting lamination occurring between PET/PU and 3D-printed PLA layer; (C) SEM image of PET/PU fibers; (D) Histogram of 200,000+ fiber diameter measurements from SEM photographs

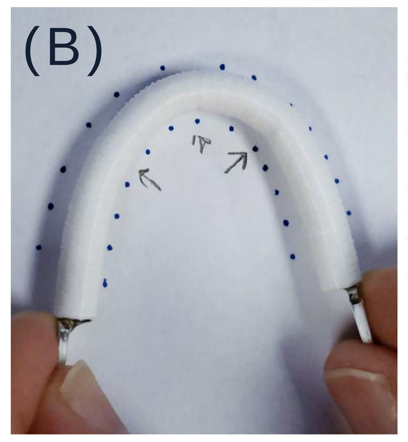
Scanning electron microscopy (SEM) images confirmed high porosity. DiameterJ measurements confirmed that fiber diameters were on the order of collagen fibers of the ECM: 54.6% of diameters fell between 121.35-364.05 nm, while 78.1% of diameters fell between 0-509.70 nm.

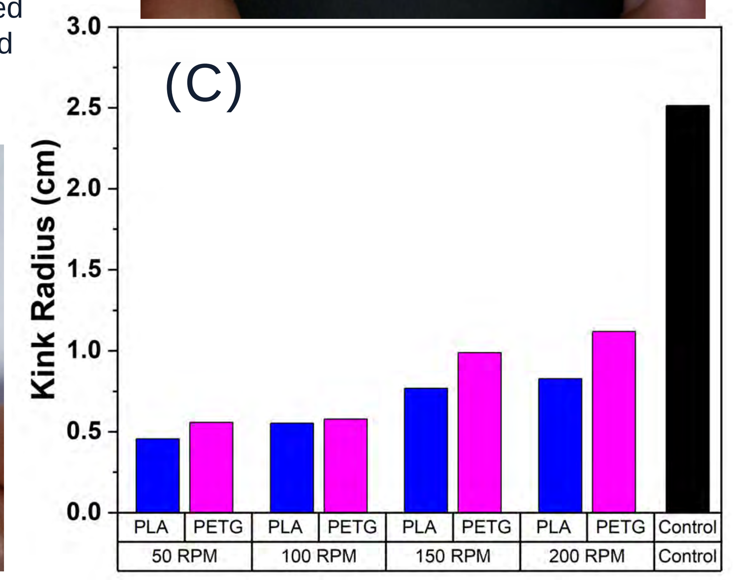
### Kink Radius

Kink radii were measured by bending samples from both ends until a bend was noticed that could occlude flow in similar way to thrombosis or stenosis [2,3]. Trends included that kink radii were higher for larger RPMs and that control grafts experienced kinking at substantially higher radii as compared to reinforced graphs.

These data clearly indicate a reduction in kink radius accompanied by reinforcement, offering a solution to small-diameter grafts that experience kinking over long distances.


Figure 6:
(A) Image depicting kinking of control graft; (B) Image depicting kinking of reinforced graft; (C) Kink radii displayed in comparative bar graph and sorted by RPM of reinforcement




## CONCLUSIONS AND FUTURE WORK

From the work completed thus far, it has been found that:

- Elastic moduli in radial direction of reinforced grafts vastly eclipses those of control grafts
- Apparent elastic moduli in longitudinal direction of reinforced grafts (notably PETG) approaches that of control grafts
- Kink radii of reinforced grafts are significantly lower than those of control PET/PU grafts
- SEM illustrate physical bonding (no delamination) between electrospun fibers and 3D-printed filaments
- Diameters of electrospun fibers are on the order of the ECM

Future work will include:

- Confirming initial conclusions with subsequent trials
- Normalizing mechanical data with materials of similar geometry having known moduli values
- Assessing biocompatibility of reinforced grafts via cell assays or *in vivo* analysis

## ACKNOWLEDGEMENTS


Support provided by the National Aeronautics and Space Administration (NASA)-Alabama Space Grant Consortium, Research Experiences for Undergraduates (REU) award to UAB. Assistance for mechanical testing provided by Jerry Sewell.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