#### Solvent-cast 3D Printing of Biodegradable Polymer Scaffolds<sup>1</sup>

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Three-dimensional (3D) printing is a popular fabrication technique because of its ability to produce complex architectures. Melt-based 3D printing is widely used for thermoplastic polymers like poly(caprolactone) (PCL), poly(lactic acid) (PLA), and poly(lactic-co-glycolic acid) (PLGA) because of their low processing temperatures. However, traditional melt-based techniques require processing temperatures and pressures high enough to achieve continuous flow, limiting the type of polymer that can be printed. Solvent-cast printing (SCP) offers an alternative approach to print a wider range of polymers. Polymers are dissolved in a volatile solvent that evaporates during deposition to produce a solid polymer filament. SCP therefore requires optimizing polymer concentration in the ink, print pressure, and print speed to achieve desired print fidelity. Here, capillary flow analysis shows how print pressure affects the process-apparent viscosity of PCL, PLA, and PLGA inks. Ink viscosity is also measured using rheology, which is used to link a specific ink viscosity to a predicted set of print pressure and print speed for all three polymers. These results demonstrate how this approach can be used to accelerate optimization by significantly reducing the number of parameter combinations. This strategy can be applied to other polymers to expand the library of polymers printable with SCP.

#### **1. Introduction**

Three-dimensional (3D) printing is a popular additive manufacturing technique due to its rapid production speed, ease of use, adaptability, and ability to produce complex architectures.<sup>[1–7]</sup> Printing methods can be grouped by how the material is processed to achieve a desired shape.<sup>[8]</sup> For example, light-assisted 3D printing, or stereolithography, uses light to cure a photopolymerizable liquid monomer into a solid polymer.<sup>[9–11]</sup> Selective laser sintering (SLS) fuses powdered particles together with a laser.<sup>[8,11,12]</sup> Melt-based techniques apply heat and pressure to extrude material through a nozzle for layer-by-layer deposition.<sup>[8,11,13]</sup> The most popular of these techniques is melt-based 3D printing, which includes fused deposition modeling (FDM) and cartridge-based 3D plotting.<sup>[8,11]</sup> FDM forces a polymer filament into a hot end to melt it for extrusion while cartridge-based 3D plotting melts polymer pellets in a cartridge before applying pneumatic or mechanical pressure to extrude the melt through a nozzle.<sup>[11,14]</sup> Melt-based 3D printing is widely used for fabricating biomaterial scaffolds using biodegradable polymers, such as poly(caprolactone) (PCL),<sup>[5–</sup> <sup>7,15,16]</sup> poly(lactic acid) (PLA).<sup>[17]</sup> and poly(lactic-co-glycolic acid) (PLGA).<sup>[11,18–21]</sup> to achieve complex, tissue-like architectures suitable for clinical translation.<sup>[8,11–14,22]</sup> These and other thermoplastic polymers have relatively low processing temperatures and can be printed using both forms of melt-based 3D printing.

Melt-based 3D printing involves heating polymers above their transition temperatures to induce flow for extrusion.<sup>[22–24]</sup> Most commercially available cartridge-based printer heads have a maximum temperature of 250 °C,<sup>[22]</sup> which limits the type of polymer that can be printed to those that can be processed below 250 °C. Limited flow due to inadequate processing temperature restricts traditional melt-based extrusion to using needles with diameters larger than 150  $\mu$ m, which constrains the potential feature sizes, resolution, and complexity that can be achieved.<sup>[25–28]</sup> An alternative approach is melt electrowriting (MEW), where voltage is used to electrostatically draw the filament during extrusion to achieve smaller filament diameters.<sup>[29–33]</sup> The resolution of MEW ranges between ~5-100  $\mu$ m, depending on the material and printing parameters used.<sup>[34]</sup> However, MEW still requires that polymers be heated to achieve flow, which limits the molecular weight and type of polymer that can be used.<sup>[34–36]</sup> Changing the molecular weight and chemically modifying the polymer affects processing temperatures and can make the polymer unprintable using melt-based techniques.<sup>[36–38]</sup> This change in processing temperature can result in poor viscous flow through the needle if a suitable printing temperature cannot be reached.<sup>[25]</sup> In addition,

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polymers are typically printed at significantly higher temperatures relative to their transition temperatures.<sup>[25,26]</sup> For example, PCL is typically heated to 120 °C to 180 °C before extruding even though its melting temperature ( $T_m$ ) is around 60 °C.<sup>[39–41]</sup> The high temperatures and pressures necessary for continuous extrusion can negatively affect material properties, such as causing unwanted polymer degradation.<sup>[42–44]</sup> These limitations with melt-based techniques point to a need for methods that do not rely on temperature and enable printing with high resolution and a wider range of polymer chemistries.

Solvent-cast 3D printing (SCP) has emerged as a promising alternative to melt-based approaches. Instead of heating to induce flow, the polymer is dissolved in a volatile solvent to produce an "ink".<sup>[45]</sup> The solvent evaporates from the ink during extrusion and leaves behind a solid polymer filament. This technique can be performed at room temperature and can be used with polymers with processing temperatures that are not suitable for existing melt-based 3D printers.<sup>[46]</sup> For example, poly(aniline) has been shown to thermally degrade before reaching its melting temperature.<sup>[47]</sup> Polv(sulfone) has a glass transition temperature (T<sub>o</sub>) of 185 °C to 190 °C and is too viscous to print with commercially available printer heads.<sup>[8,47]</sup> Both of these polymers have been successfully printed using SCP.<sup>[14,41]</sup> An additional advantage is that SCP has been shown to produce scaffolds with smaller feature sizes compared to scaffolds printed using traditional melt-based extrusion.<sup>[38,48,49]</sup> We previously used SCP to produce PCL-based scaffolds with filament diameters as small as 38.5 µm, which is comparable to filament diameters (~5-100  $\mu$ m) that can be achieved by MEW.<sup>[34,38,50]</sup> However, scaffolds fabricated using SCP may have residual solvent, which would limit in vivo and clinical translation. PCL scaffolds fabricated using SCP have been seeded with fibroblasts<sup>[38]</sup> and human mesenchymal stem cells<sup>[50,51]</sup> without causing adverse effects on cell response. These results indicate that SCP is a suitable technique for fabricating scaffolds for biomedical applications.

Similar to other 3D printing methods, SCP print parameters must be optimized to obtain a desired final shape.<sup>[13,52–56]</sup> Print pressure, print speed, and ink properties are all related to the volumetric flow of the ink, which influences print fidelity.<sup>[13]</sup> Print pressure controls the volume of ink that is extruded, while print speed relative to the volumetric flow rate must be controlled to maintain the shape of the extrudate. At the same time, the solvent content in the extruded ink must be minimized to ensure rapid solvent evaporation to achieve shape fidelity.<sup>[14,48,57]</sup> The ink must have a low enough polymer concentration to enable flow

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through the needle and a high enough polymer concentration to avoid losing the extruded shape.<sup>[57]</sup> Guo et al. showed that a minimum PLA concentration was required to 3D print freestanding structures like vertical spirals using SCP.<sup>[48]</sup> They showed that one-dimensional filaments could be produced with a wide range of PLA concentrations, but two-dimensional arrays or 3D layer-by-layer scaffolds required inks with a lower solvent content.<sup>[57]</sup> Polymer concentration also requires changes to print pressure and print speed to compensate for the change in ink properties, significantly increasing the print parameter space. For example, we previously identified a suitable PCL-based ink for SCP by systematically varying PCL concentration, print pressure, and print speed.<sup>[38]</sup> Each time the polymer concentration was modified, print pressure and print speed had to be adjusted due to changes in solvent evaporation and shape fidelity. We therefore wanted to identify strategies to reduce the parameter space and optimization time.

We hypothesized that ink properties are related to a specific combination of print pressure and print speed during SCP, regardless of the type of polymer being printed. To test this, we investigated how shape fidelity was affected by three key parameters: print speed, print pressure, and polymer concentration in the ink. We characterized ink properties by matching shear rates observed during process-related volumetric flow to parallel plate rheology. We then used rheology to select inks with polymer concentrations that achieved a specific viscosity at a given shear rate. This strategy enabled us to use the rheological properties of each polymer ink to predict a suitable print speed and print pressure without requiring iterative optimization steps. This approach can be applied with other polymers to increase the use and accessibility of SCP.

#### 2. Results and Discussion

#### 2.1 Effect of Print Speed and Print Pressure on Filament Morphology

Based on our previous work with poly(caprolactone) (PCL), we selected an ink containing 370 mg ml<sup>-1</sup> PCL in 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP) to investigate the effect of print pressure and print speed on filament shape.<sup>[38,50]</sup> Specifically, we observed how the printed filament maintained the cylindrical morphology of the extrudate and needle. We saw significant differences in filament shape with different print speeds and print pressures. We found that shape fidelity was improved at print pressures and print speeds that enabled fast solvent evaporation. Other groups showed similar results where one-dimensional filaments could be produced with a wide range of PLA concentrations, but two-dimensional arrays or

3D layer-by-layer scaffolds required inks with a lower solvent content.<sup>[48,57]</sup> Higher print pressures resulted in a larger amount of total ink volume extruded, which required more time for solvent evaporation and therefore resulted in a flattened filament shape (Figure 1). Lower print speeds also increased the total volume extruded and produced flattened morphologies (Figure 2). Reducing the volume coming out of the needle by decreasing print pressure or increasing print speed successfully produced consistent cylindrical morphologies. However, the lower print pressures of 42 and 56 psi and higher print speeds of 0.8 and 1.0 mm s<sup>-1</sup> caused the filament to lose contact with the substrate. In these cases, the extruded ink volume was too low, resulting in the filament being stretched between contact points with the substrate. We selected printing the 370 mg ml<sup>-1</sup> PCL ink with a combination of 0.4 mm s<sup>-1</sup> and 70 psi for based on these results and in agreement with our previous work.<sup>[38,50]</sup> It should be noted that print pressure and print speed can be continuously adjusted to counterbalance each other, but this creates an inefficient and tedious process that changes with each new ink composition.<sup>[52,58]</sup> We hypothesized that ink properties are linked to a narrow range of print pressures and print speeds and therefore characterized the rheological properties of different polymer-based inks.



**Figure 1**. Scanning electron microscopy (SEM) images of filaments 3D printed with 370 mg ml<sup>-1</sup> PCL at a constant print speed of 0.4 mm s<sup>-1</sup> with varying print pressures. Decreasing print pressure resulted in filament stretching and detachment from the glass substrate while increasing print pressure led to flattened morphologies.



**Figure 2**. Scanning electron microscopy (SEM) images of filaments 3D printed with 370 mg ml<sup>-1</sup> PCL at a constant print pressure of 70 psi with varying print speeds. Increasing print speed resulted in filament stretching and detachment from the glass substrate while decreasing print speed produced flattened morphologies.

#### 2.2 Relationship between Print Parameters and Ink Viscosity

Volumetric flow measurements were used to determine the process-related apparent viscosity, which provided insight to how the ink responds during the printing process.<sup>[48,59]</sup> The processrelated apparent viscosity of the 370 mg ml<sup>-1</sup> PCL ink was used to calculate shear rates to match a set of known print parameters (Figure 3). Calculated shear rates of 5.3, 9.0, 23.2, 35.5 s<sup>-1</sup> related to print pressures of 56, 70, 140, and 210 psi, respectively (Table S2). As expected, an increase in shear rate resulted in a decrease in the process-related apparent viscosity. We used rheology to measure ink viscosity at the calculated shear rates and plotted the data together to directly compare the two methods (Figure 3). Trendlines fitted to both plots indicated shear-thinning behavior. Although the values were within a standard deviation, the process-related apparent viscosity appeared to be higher than the measured viscosity at all shear rates. This variation was likely due to two key assumptions made in the volumetric flow calculations when converting the measured mass to volume: (1) the extruded ink was a perfect cylinder; and (2) the actual polymer concentration in the ink matched the intended concentration. These assumptions likely underestimate the actual extruded volume, resulting in a higher calculated process-related apparent viscosity compared to values directly measured using rheology. The volumetric flow method is also a time-consuming process because significant amounts of ink must be extruded to deposit enough polymer that can be massed accurately. This approach can take multiple hours depending on the pressure being used, whereas rheology can be performed in a few minutes. Overall, these data showed that rheology can be used to predict the process-related apparent viscosity at a given shear rate. We used rheology for subsequent experiments to characterize the viscosity of inks containing different polymer concentrations at selected shear rates.



**Figure 3.** Log viscosity (Pa·s) versus log shear rate (s<sup>-1</sup>) showing shear-thinning behavior of 370 mg ml<sup>-1</sup> PCL ink measured using volumetric flow (open circles) and rheology (closed circles) (N=4 per shear rate; error bars representing standard deviation).

#### 2.3 Effect of Ink Concentration on Viscosity

We investigated how polymer concentration affected the rheological properties of the ink to understand more about their response during printing. We first characterized inks containing 300, 350, 370, and 400 mg ml<sup>-1</sup> PCL at shear rates ranging from 3.0 to 30 s<sup>-1</sup>. As expected, ink viscosity increased with increasing PCL concentration at all shear rates (**Figure 4**).<sup>[60]</sup> The log-log trendlines showed negative slopes indicating shear-thinning behavior at all PCL concentrations.



**Figure 4.** Log viscosity (Pa·s) versus log shear rate ( $s^{-1}$ ) of poly(caprolactone) (PCL) inks at different concentrations. Increasing PCL concentration in the ink corresponded with an increase in viscosity at all shear rates.

#### 2.4 Effect of Polymer Concentration on Scaffold Morphology

We printed scaffolds using inks containing 300, 350, 370, and 400 mg ml<sup>-1</sup> PCL using the same print pressure (70 psi) and print speed (0.4 mm s<sup>-1</sup>) to observe how ink viscosity independently affected filament shape. These print parameters were optimized empirically for the 370 mg ml<sup>-1</sup> PCL ink in prior work<sup>[38]</sup> and shown in Figures 1 and 2 to produce a consistent filament shape.<sup>[50]</sup> We measured the filament diameter and cross-sectional roundness to compare changes in filament shape based on ink composition. Roundness values close to one indicated a circular cross-section and a cylindrical filament morphology similar to the extrudate.<sup>[61]</sup> We considered roundness values of 0.85 or greater to indicate successful print fidelity. Initial layers showed flattened morphologies due to increased wetting of the polymer to the glass printing substrate. Wetting was also observed at junctions between filaments printed with lower PCL ink concentrations due to the lower ink viscosities (**Figure 5**). Roundness measurements were therefore measured using sectioned filaments between junctions near the top of the scaffold away from the substrate to avoid these wetting effects.

Scaffolds printed with the lowest PCL concentration showed the largest filament diameters (**Figure 5**). As the PCL concentration in the ink increased, the filament diameter and cross-section shape changed significantly (Figure 5). Inks with higher polymer concentrations and therefore higher viscosities (Figure 4) reduced the volumetric flow of ink extruded (**Figure 5E**). For example, increasing the PCL concentration from 300 to 400 mg ml<sup>-1</sup> resulted in a significant decrease in filament diameter from  $50.74 \pm 2.70 \,\mu$ m to  $27.02 \pm 2.56 \,\mu$ m and roundness from 0.9 to below 0.8, respectively (Figure 5). The decrease in volumetric flow (Figure 5E) correlated with a decrease in filament diameter and cross-sectional roundness, indicating reduced shape fidelity. Increasing polymer concentration in the ink resulted in a higher viscosity (Figure 4) that reduced the volume extruded. These data demonstrated how ink viscosity directly affected shape fidelity.<sup>[62]</sup> Notably, 350 and 370 mg ml<sup>-1</sup> PCL inks showed similar viscosities (Figure 4) and resulted in statistically similar filament diameters and roundness values. This result confirmed that inks with similar rheological behavior can be printed with the same print parameters and result in similar fiber diameters and cross-sectional roundness.

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**Figure 5.** Representative SEM images of scaffolds printed with inks containing (A) 300, (B) 350, (C) 370, and (D) 400 mg ml<sup>-1</sup> PCL. Inset images show representative cross-sections of individual filaments (scale bar =  $20 \ \mu$ m). All scaffolds were printed using the same print pressure, print speed, and print pattern. Changes in PCL concentration in the ink resulted in changes in (E) filament diameter ( $\mu$ m), shown by clustered data points, (N=5 scaffolds per group, 8 measurements per scaffold) and volumetric flow (cm<sup>3</sup> s<sup>-1</sup>), shown in bar graph, and (F) roundness (N = 5 scaffolds per group, 5 measurements per scaffold). A one-way ANOVA comparing all groups was performed with significance indicated by \*p<0.05. The asterisk (\*) represents significance against all other groups unless noted as not significant (ns).

#### 2.5 Characterizing Viscosity of PLGA and PLA Inks

We applied the same techniques to inks containing different polymers to demonstrate how a selected ink viscosity can be linked to a specific set of print parameters. We measured the viscosity of PLGA and PLA inks with different polymer concentrations using rheology and found that increasing polymer concentration resulted in higher viscosity across all shear rates (**Figure 6**). The negative log-log trendlines showed shear-thinning behavior for both polymers at all concentrations. The 450 mg ml<sup>-1</sup> PLGA and 270 mg ml<sup>-1</sup> PLA inks had viscosities that closely matched the viscosity of the 370 mg ml<sup>-1</sup> PCL ink between shear rates from 3.0 to 10 s<sup>-1</sup> (**Figure 6C**). Shear rates from 5.0 to 10 s<sup>-1</sup> are of particular interest because their corresponding pressures are easily achievable on commonly available printing platforms.<sup>[63–65]</sup> We therefore selected these inks to print scaffolds using the same print pressure and print speed used in Figure 5.



**Figure 6.** Log viscosity (Pa·s) versus log shear rate (s<sup>-1</sup>) showing shear-thinning behavior of inks containing different concentrations of (A) poly(D,L-lactide-co-glycolide) (PLGA) and (B) poly(D,L-lactic acid) (PLA). Increasing polymer concentration resulted in a corresponding increase in viscosity. (C) Graph showing matching viscosities between 370 mg ml<sup>-1</sup> poly(caprolactone) (PCL), 270 mg ml<sup>-1</sup> poly(D,L-lactic acid) (PLA), and 450 mg ml<sup>-1</sup> poly(D,L-lactide-co-glycolide) (PLGA) in HFIP from shear rates ranging from 3.0 to 10 s<sup>-1</sup>.

#### 2.6 Characterizing PLGA and PLA Scaffold Morphology

We printed 450 mg ml<sup>-1</sup> PLGA and 270 mg ml<sup>-1</sup> PLA inks using the same print pressure (70 psi) and print speed (0.4 mm s<sup>-1</sup>) as the PCL inks (**Figure 7**). Filaments printed with the PLGA and PLA inks resulted in larger diameters  $48.08 \pm 1.66 \,\mu\text{m}$  and  $52.27 \pm 1.50 \,\mu\text{m}$ , respectively, compared to 370 mg ml<sup>-1</sup> PCL ( $36.88 \pm 4.04 \,\mu\text{m}$ ) (**Figure 7C**) and were statistically different from each other. This difference in filament diameter can be attributed to

differences in polymer molecular weight and concentration in the ink. Notably, both PLGA and PLA inks produced filaments with roundness values of 0.85 and higher indicating successful shape fidelity and showed no statistical differences from each other (**Figure 7D**). Printing the other concentrations of PLGA and PLA inks with the same print pressure and print speed showed similar effects on shape fidelity seen with PCL inks (**Figures S5 and S6**). These results confirmed that the relationship between ink viscosity and print parameters can be applied to reduce optimization steps and parameter space to achieve reproducible architectures with SCP.



**Figure 7**. Representative SEM images of scaffolds 3D printed with (A) 450 mg ml<sup>-1</sup> PLGA and (B) 270 mg ml<sup>-1</sup> PLA with inset images showing representative cross-section of the printed filament. (C) Filament diameter ( $\mu$ m) (N=5 scaffolds per group, 8 measurements per scaffold) and (D) roundness measurements (N = 5 scaffolds per group, 5 measurements per scaffold) showed uniform, reproducible filament morphologies and no significant difference. A two-tailed t-test comparing groups was performed on the filament diameter and roundness data with significance indicated by \*\*p<0.001. The asterisks (\*\*) represents significance against groups and no mark represents no significance.

#### **3.** Conclusion

Solvent-cast 3D printing (SCP) offers an exciting technique to fabricate constructs with high resolution and complex architectures that can be used with polymers that are not compatible with traditional melt-based techniques. Polymer concentration in the ink influenced the volumetric flow rate and resulting print fidelity due to the change in process-related apparent viscosity. This work demonstrated that rheology can be used to identify a suitable ink viscosity for a predicted set of print pressure and print speed to achieve desired shape. We used this approach successfully with different biodegradable polymers, illustrating the ability to pre-determine optimal solvent-cast printing conditions and significantly reduce the

potential parameter space. Future work includes printing scaffolds with medical grade polymers to accelerate this technique towards clinical translation. This strategy can be applied to a wide range of polymer-solvent combinations to expand the library of printable polymers to those that cannot be printed with melt-based 3D printing. In addition, different polymers can be combined within the same scaffold to mimic the anisotropic biochemical and physical properties of native tissues.

#### 4. Methods

*Ink Preparation*: Poly(caprolactone) (PCL; 80 kg/mol), poly(D,L-lactide-co-glycolide) (PLGA; 50:50 lactide:glycolide; inherent viscosity (IV) 1.0 dL/g), and poly(D,L-lactic acid) (PLA; 450 kg/mol) were provided by Polysciences, Inc. (Warrington, PA, USA).<sup>2</sup> Each polymer was dissolved in 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP; Matrix Scientific, Columbia, SC, USA) at pre-defined concentrations to produce inks for printing. Inks were sealed in a syringe and mixed on a wrist-action shaker for 48 hours. Once the polymer was fully dissolved, inks were stored without agitation for at least 24 hours before printing or characterizing.

Solvent-Cast 3D Printing: Inks were 3D printed using pneumatic extrusion on a 3-axis EV Series Automated Dispensing System (Nordson EFD, East Providence, RI, USA). Syringes were fitted with a 32G blunt-tip needle (100  $\mu$ m inner diameter) and inserted in an HP3cc Dispensing Tool (Nordson EFD), which increased the applied pressure by seven-fold. Inks were deposited onto glass slides and left in a fume hood overnight to allow complete solvent evaporation before characterizing. Filaments were printed with print pressures ranging from 70 to 280 psi and print speeds ranging from 0.1 to 1.0 mm s<sup>-1</sup>. Glass slides were coated with hairspray before printing scaffolds. Scaffolds were printed in orthogonal patterns with 260  $\mu$ m programmed filament spacings using a print pressure of 70 psi and print speed of 0.4 mm s<sup>-1</sup> for the first layer and 0.2 mm s<sup>-1</sup> for all subsequent layers. Scaffolds were printed with zspacing of 45  $\mu$ m for all layers until 24 layers were printed.

*SEM Imaging*: Prints were imaged using a LEO 1550 scanning electron microscope (SEM; Zeiss, Peabody, MA, USA). Sectioned scaffolds were stored at -20 °C for 24 hours before cutting with a polytetrafluoroethylene (PTFE)-coated razor. Samples were mounted on 12-mm aluminum sample stubs with carbon tape and coated with 10 nm iridium using a sputter coater (Electron Microscopy Sciences EMS575X, Hatfield, PA, USA) before imaging.

*Filament Measurements*: SEM images of scaffolds and scaffold cross-sections were used to determine filament diameter and roundness. Filament diameter and roundness were measured manually using the open-source program ImageJ (**Figure S1**). For filament diameter, eight measurements were averaged for each scaffold (N=5 scaffolds per polymer concentration) (**Figure S1A**). Roundness was determined by tracing the outline of the filament cross-section (**Figure S1B**). A total of five filament cross-sections were analyzed from each scaffold (N=5 scaffolds per polymer concentration). Roundness was calculated using Equation 1:<sup>[61]</sup> *Roundness* =  $C_I$  + (0.913 -  $C_{AR}$ ) (1).

Filament diameter, roundness, and mean and standard deviation of the measured object are reported in **Table S1**. A one-way ANOVA followed by a Tukey post-hoc (N=5) comparing all groups was performed for filament diameter and roundness with statistically significant differences indicated by p<0.05. A two-tailed t-test comparing groups was performed on the PLGA and PLA filament diameter and roundness data with significance indicated by p<0.001. Statistical analysis was carried out in Prism (Version 9, GraphPad Software, USA).

*Capillary Flow Analysis*: Capillary flow analysis<sup>[48,57,59]</sup> was conducted with PCL inks to determine its process-related apparent viscosity. All inks were extruded through a 32G blunttip needle with length (L) 6.35 mm and radius (R) 50  $\mu$ m with a constant print speed of 0.4 mm s<sup>-1</sup>. The 300, 350, 370, and 400 mg ml<sup>-1</sup> inks were tested at 70 psi. The 370 mg ml<sup>-1</sup> ink was tested at pressures of 56, 70, 140, and 210 psi. The printed material was weighed to determine mass flow rate, which was converted to volumetric flow rate (Q) based on the expected polymer concentration in the ink. The wall shear stress ( $\tau_w$ ) was calculated with atmospheric pressure ( $P_a$ ), the applied print pressure ( $P_{appl}$ ), and aspect ratio (L/R) using Equation 2: <sup>[48,57,59]</sup>

$$\tau_w = \frac{P_{appl} - P_a}{2\left(\frac{L}{R}\right)} \tag{2}.$$

The Newtonian shear rate ( $\dot{\gamma}_{Newt}$ ) was calculated using the measured volumetric flow rate Q and needle radius (R), as shown in Equation 3: <sup>[48,57,59]</sup>

$$\dot{\gamma}_{Newt} = \frac{4Q}{\pi R^3} \tag{3}$$

The Rabinowitch correction (Equation 4), <sup>[48,57,59]</sup> where b is the slope of a log-log plot of Newtonian shear rate and shear stress, was applied to convert  $\dot{\gamma}_{Newt}$  to wall shear rate  $(\dot{\gamma}_W)$  and account for Non-Newtonian effects:

$$\dot{\gamma}_W = \dot{\gamma}_{Newt} \left(\frac{3+b}{4}\right) \tag{4}$$

The process-related apparent viscosity  $(\eta_{app})$  was calculated using Equation 5: <sup>[48,57,59]</sup>

 $\eta_{app} = \frac{\tau_w}{\dot{\gamma}_w} \tag{5}.$ 

Process-related apparent viscosity was plotted as a function of calculated shear rates and compared to viscosities measured using rheology. Relevant data can be found in Table S2.

*Rheology*: Inks were prepared with each polymer dissolved in HFIP at the following concentrations: 300, 350, 370, and 400 mg ml<sup>-1</sup> PCL; 450, 470, and 500 mg ml<sup>-1</sup> PLGA; and 250, 270, and 300 mg ml<sup>-1</sup> PLA. Rheology was performed on each ink at room temperature using a Discovery Hybrid Rheometer (DHR; TA Instruments, New Castle, DE, USA) fitted with a modified parallel plate fixture (25 mm diameter top plate, 40 mm diameter bottom plate) at a geometry gap distance of 500  $\mu$ m. Samples (250  $\mu$ L) were added directly to the bottom plate before lowering the top plate to a trim gap of 600  $\mu$ m. Excess ink outside the top plate boundary was removed before lowering the plate to 500  $\mu$ m. All ink concentrations were characterized using a flow sweep test with shear rates ranging from 3.0 s<sup>-1</sup> to 30 s<sup>-1</sup>. Notably, individual inks (N = 3-5 per shear rate) were tested at each shear rate to avoid solvent evaporation effects. As shown in Figures S2-S4, all data were collected after the stress overshoot, and the viscosity was averaged across the stable stress plateau. Collected data were plotted as average viscosity as a function of shear rate with error bars representing one standard deviation.

#### **Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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#### **Additional References**

<sup>1</sup> Official contribution of the National Institute of Standards and Technology; not subject to copyright in the United States.

<sup>2</sup> Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

### Supporting Information

#### Solvent-cast 3D Printing of Biodegradable Polymers

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#### **Filament Measurements**

Scaffolds were placed in a -20 °C freezer for 24 hours before sectioning with a poly(tetrafluoroethylene) (PTFE)-coated razor blade. Sectioned samples were mounted on an aluminum stub using carbon tape and sputter-coated (Electron Microscopy Sciences EMS575X, Hatfield, PA, USA) with 10 nm iridium before imaging with a scanning electron microscope (SEM) (LEO 1550 SEM; Zeiss, Peabody, MA, USA). Filament diameter, area, and perimeter were measured from the SEM images using ImageJ. Filament diameter was averaged based on the length of eight line segments drawn across the filament cross-section using ImageJ (**Figure S1A**). Roundness was calculated by manually tracing an outline of the filament cross-section and using the area and perimeter reported from ImageJ (**Figure S1B**). Filament diameter and roundness measurements were averaged across five filaments per scaffold for a total of five scaffolds per group.



**Figure S1.** Representative scanning electron microscopy (SEM) image of the cross-section of a filament 3D printed with 370 mg ml<sup>-1</sup> poly(caprolactone) (PCL). (A) Eight line segments (yellow) were drawn across the filament to determine filament diameter. (B) An outline (yellow) of the filament cross-section was used to measure the area and perimeter to calculate roundness.

**Table S1.** Filament diameter, mean and standard deviation, and roundness of the measured

 filament shown in Figure S1.

|                        | 31.8         | 36.1 | 40.3 | 37.7 | 34.1 | 36.1 | 33.9 | 36.4 |
|------------------------|--------------|------|------|------|------|------|------|------|
| Filament diameter (µm) | 9            | 1    | 5    | 6    | 4    | 8    | 3    | 9    |
| Mean ± SD (µm)         | 35.86 ± 2.59 |      |      |      |      |      |      |      |
| Roundness              |              |      |      | 0.8  | 346  |      |      |      |

#### **Capillary Flow Analysis**

**Table S2.** Relevant data used to determine shear rate and process-related apparent viscosity shown in Figure 3.

| Pressure Applied (psi)   | 56  | 70  | 140   | 210  |
|--|---|---|---|--|
| Needle Length, L (mm)  | 6.35  | 6.35  | 6.35  | 6.35   |
| Needle Radius, R (mm)  | 0.05  | 0.05  | 0.05  | 0.05   |
| Mass (mg)  | 1.4   | 2.6   | 7.2   | 9.4  |
| Density (g/cm <sup>3</sup> )   | 370   | 370   | 370   | 370  |
| Time (s)   | 7500  | 7500  | 7500  | 7500   |
|  |   |   |   |  |
| Q (cm <sup>3</sup> /s)   | 4.86 x 10 <sup>-7</sup>                                     | 9.44 x 10 <sup>-7</sup>                                     | 2.59 x 10 <sup>-6</sup>                                       | 3.4 x 10 <sup>-6</sup>   |
| Q (cm <sup>3</sup> /s)<br>Shear Stress (psi) <sup>[1,2,3]</sup>  | 4.86 x 10 <sup>-7</sup><br>0.1626                           | 9.44 x 10 <sup>-7</sup><br>0.2177                           | 2.59 x 10 <sup>-6</sup><br>0.4933                             | 3.4 x 10 <sup>-6</sup><br>0.7689   |
| Q (cm <sup>3</sup> /s)<br>Shear Stress (psi) <sup>[1,2,3]</sup><br>Shear Stress (Pa)   | 4.86 x 10 <sup>-7</sup><br>0.1626<br>1121.2                 | 9.44 x 10 <sup>-7</sup><br>0.2177<br>1501.2                 | 2.59 x 10 <sup>-6</sup><br>0.4933<br>3401.3                   | 3.4 x 10 <sup>-6</sup><br>0.7689<br>5301.5                               |
| Q (cm <sup>3</sup> /s)<br>Shear Stress (psi) <sup>[1,2,3]</sup><br>Shear Stress (Pa)<br>Shear Rate (1/s) <sup>[1,2,3]</sup>  | 4.86 x 10 <sup>-7</sup><br>0.1626<br>1121.2<br>4.96         | 9.44 x 10 <sup>-7</sup><br>0.2177<br>1501.2<br>9.62         | 2.59 x 10 <sup>-6</sup><br>0.4933<br>3401.3<br>26.35          | 3.4 x 10 <sup>-6</sup> 0.7689         5301.5         34.61               |
| Q (cm <sup>3</sup> /s)<br>Shear Stress (psi) <sup>[1,2,3]</sup><br>Shear Stress (Pa)<br>Shear Rate (1/s) <sup>[1,2,3]</sup><br>Corrected Shear Rate (1/s) <sup>[1,2,3]</sup> | 4.86 x 10 <sup>-7</sup><br>0.1626<br>1121.2<br>4.96<br>5.28 | 9.44 x 10 <sup>-7</sup><br>0.2177<br>1501.2<br>9.62<br>8.96 | 2.59 x 10 <sup>-6</sup><br>0.4933<br>3401.3<br>26.35<br>23.22 | 3.4 x 10 <sup>-6</sup> 0.7689         5301.5         34.61         35.53 |

#### **Stress Growth Experiment**

Stress growth experiments were performed by applying a constant shear rate for 180 s. Stress and viscosity were plotted together so that only data after the stress overshoot is averaged (**Figure S2**). The region highlighted in the black boxes indicate where data was averaged. Additionally, data needed to be collected before evaporation, wall slip, or edge fracture affected the sample. PCL (**Figure S2**), PLGA (**Figure S3**), and PLA (**Figure S4**) inks were

tested using this method at for every concentration and at each shear rate shown in the figures in the main text.



**Figure S2.** Representative stress (MPa) and viscosity (Pa·s) as a function of step time (s) for 370 mg ml<sup>-1</sup> PCL tested at a constant shear rate of 5 s<sup>-1</sup>. The highlighted region (black box) represents the range of viscosity values that were averaged to obtain the reported viscosity.



**Figure S3.** Representative stress (MPa) and viscosity (Pa·s) as a function of step time (s) for 450 mg ml<sup>-1</sup> poly(lactic-co-glycolic acid) (PLGA) tested at a constant shear rate of 5 s<sup>-1</sup>. The highlighted region (black box) represents the range of viscosity values that were averaged to obtain the reported viscosity.



**Figure S4.** Representative stress (MPa) and viscosity (Pa $\cdot$ s) as a function of step time (s) for 270 mg ml<sup>-1</sup> poly(lactic acid) (PLA) tested at a constant shear rate of 5 s<sup>-1</sup>. The highlighted region (black box) represents the range of viscosity values that were averaged to obtain the reported viscosity.

#### SEM of PLGA and PLA scaffolds

PLGA and PLA at all concentrations were also printed to confirm similar behavior to the PCL inks. The 500 mg ml<sup>-1</sup> PLGA scaffold resembles the stretched fibers of the 400 mg ml<sup>-1</sup> PCL. While the 470 mg ml<sup>-1</sup> PLGA fibers look similar to the 450 mg ml<sup>-1</sup> PLGA, this is likely because small differences in concentration do not affect fiber morphology, as shown by the lack of statistical difference in filament diameter and roundness between scaffolds printed with 350 and 370 mg ml<sup>-1</sup> PCL inks.



**Figure S5**. Representative SEM images of scaffolds printed with inks containing (A) 500 mg ml<sup>-1</sup> and (B) 470 mg ml<sup>-1</sup> poly(lactic-co-glycolic acid) (PLGA).



**Figure S6**. Representative SEM images of scaffolds printed with inks containing (A) 300 mg ml<sup>-1</sup> and (B) 250 mg ml<sup>-1</sup> poly(lactic acid) (PLA).

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