Auxetic tubular scaffolds via melt electrowriting

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ABSTRACT

Auxetics are an interesting class of materials that expand in transverse directions when tensile loading is applied. For example, in contrast to conventional materials, an auxetic tube will increase in diameter when stretched along its axis. To date, auxetic tubular scaffolds have been proposed for applications in tissue engineering and soft robotics; however, they have not yet been routinely produced in precisely-engineered microfibre structures using the melt electrowriting additive manufacturing method. Using a custom melt electrowriting device and rotating mandrel collector, scaffolds with a re-entrant honeycomb unit cell pattern were designed and fabricated from polycaprolactone microfibres. These scaffolds were tensile tested to characterise their auxetic properties compared to traditional crosshatch-patterned tubular scaffolds. The auxetic scaffolds exhibited an increase in diameter up to 80.8%, as predicted from the unit cell pattern at maximum strain of 14.1%, resulting in a Poisson’s ratio of $-5.8$. By comparison, crosshatch scaffolds exhibited a similar stress-strain profile to the auxetic tubular scaffold with identical pore size, however significant radial compression was observed leading to a Poisson’s ratio of $+5.7$. This study reports the design and fabrication of auxetic tubular microfibre scaffolds fabricated via melt electrowriting for the first time and offers a versatile fibre patterning system towards applications in biofabrication and robotics.

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Materials typically contract in directions perpendicular to applied forces. This behaviour is characterised by a positive Poisson’s ratio which is the ratio of contracting transverse strain to axial tensile strain.

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Conversely, auxetic materials and structures exhibit unusual deformation properties as they expand rather than contract under tensile loading which is known as a negative Poisson's ratio [1]. Using additive manufacturing for applications in tissue engineering and soft robotics, auxetic behaviour can be created through accurate placement of fibres in patterns which typically undergo an unfolding or untangling process under tensile load to generate expansion in one or more axes [2]. Herein, we report for the first time the fabrication of microfibre auxetic tubular scaffolds produced using melt electrowriting.

Melt electrowriting (MEW) is a promising additive manufacturing technique which is gaining traction in the fields of tissue engineering, biofabrication and soft robotics for the production of precision microfibre structures with control of the internal microarchitecture in addition to external shape [3,4]. By combining elements of electrohydrodynamic processing with a motorised computer-driven collector system, microfibres are generated by flowing a stable stream of polymer melt which can be deposited into highly-controlled 3D structures, often referred to as scaffolds in the context of tissue engineering [5]. As shown previously, tubular structures can be fabricated by adapting this additive manufacturing hardware to include a rotating mandrel instead of a flat collector plate [5,6]. For tubular scaffolds, patterning to date has been limited to crosshatch or diamond shaped fibre structures. Herein, we demonstrate the ability to fabricate tubular microfibre scaffolds with a negative Poisson's ratio leading to elastic radial expansion under tensile loading, compared to the typical contraction behaviour of basic crosshatch scaffold architecture which acted as a control group [7].

A custom-built MEW device, described previously [7,8], was used to fabricate scaffolds from polycaprolactone (CAPA 6430, M_w = 37 kDa, Perstorp, Sweden) heated to 90 °C and extruded at 0.05 MPa through a 21 G nozzle (Nordson, USA). Fibres were collected onto a rotating mandrel with horizontal translation; the combined movement of the collector with respect to the needle was kept constant at 100 mm/min. Machine control instructions (g-code) were written to guide the fabrication of 8 mm diameter, 48 mm length and 5 layer high scaffolds with a re-entrant honeycomb unit cell design. Unit cells 5 mm in height with widths of 8 mm and 16 mm were created by printing consecutive radial columns of one side of the honeycomb pattern before translating laterally along the mandrel to print the next half pattern until the entire length of the scaffold was complete. A final zig-zag line was then printed to complete the remaining pattern with the next layer commencing back at the origin, as depicted in Supplementary Data A. Control scaffolds were created with a crosshatch design and g-code was generated with an identical laydown angle and pore size to that of the aforementioned 5 × 8 mm auxetic design; 60° laydown angle, 20 mm² pore area, 8 mm diameter, 48 mm length and 5 layers high [7]. Scaffolds were affixed to custom 3D printed circular mounts and tensile mechanical testing was performed in using a Tytron 250 Microforce Testing System (MTS Systems Corp., USA) using a load cell (Model 6 61. 098-22) with 2.5 mN resolution, calibrated at ±25 N and ±2.5 N. A camera was also fitted above the testing rig on standard video quality mode (iPhone 7 Plus, 2016 release, Apple, USA) to visualise deformation during tensile testing. Stress-strain curves were calculated from the force-displacement data by dividing the force by the average cross-sectional area of the scaffolds, equal to a circle of radius 4.257 mm minus the 4 mm radius circular void in the centre, and normalising the strain to initial displacement. Measurements were performed in triplicate and reported as average ± standard deviation.

Based on the unit cell design, the longitudinal scaffold strain at which the honeycomb pattern is fully unfolded can be calculated by (1 − sin β), whereby β is the angle subtended by the circumferential vertical lines and diagonal horizontal lines. Additionally, the circumferential expansion upon tensile loading is driven by the radial displacement of the vertical fibres struts, which is shown in Supplementary Data B. The maximum extension of circumference occurs when the horizontal diagonal struts unfold and align with the axis of the tube. It was therefore predicted that both the auxetic scaffolds would exhibit a 71.6% increase in diameter since the radial height of the unit cells was kept constant. After complete unfolding, the vertical fibres would be uniformly shifted and expanded despite the variation in unit cell width. The width of the unit cell was predicted to instead influence the longitudinal scaffold strain at which the re-entrant honeycomb pattern was fully unfolded. This maximum strain was predicted to be 14.7 ± 0.4% and 3.9 ± 0.7% for the 5 × 8 mm and 5 × 16 mm scaffolds respectively. The experimental results closely matched these theoretical values, whereby the diameter of the scaffolds increased by 80.8% and 66.3% during loading up to 14.1% and 4.7% maximum strain for each scaffold design respectively, as shown in a video of the tensile tests in Supplementary Data C. The experimental results closely correlated with the predicted deformation behaviour, considering the observable diameter of the tubular scaffolds may vary up to 10% due to the angle at which the scaffold’s unit cell lattice is viewed, described in Supplementary Data D. Therefore, the measured increase in diameters fell within the predicted 71.6–88.7% range, validating the accurate fabrication of melt electrowritten auxetic tubular scaffolds using a re-entrant honeycomb pattern.

Comparatively, the crosshatch scaffold with the same unit cell pore area and laydown angle as the 5 × 8 mm auxetic scaffold exhibited the expected contraction of the crosshatch structure under tensile loading, depicted in Supplementary Data C, with a near-identical stress-strain profile. Considering that the 5 × 8 mm auxetic and crosshatch scaffolds were designed with the same number of fibres at the same laydown angle, it was expected that the longitudinal tensile behaviour in the linear elastic region would be identical, despite the different geometry. However, their differing geometry was validated by calculating the Poisson’s ratio. It was found that Poisson’s ratio of the auxetic pattern was −5.8 compared to the crosshatch scaffold of +5.7, calculated in Supplementary Data E. Additional research into the biaxial properties of these scaffolds would further inform the similarities and differences in mechanical properties of auxetic versus crosshatch scaffold geometries.

This study represents the first-reported auxetic tubular scaffold manufacturing via melt electrowriting. These scaffolds have promising applications in tissue engineering such as for oesophagus [9] and cardiovascular applications [10], whereby scaffolds which increase in diameter during tensile loading may assist in resisting blood vessel collapse. Additionally, these scaffolds may be useful in soft robotics, and further contribute to the growing library of MEW scaffold patterns.

**CRediT authorship contribution statement**

Naomi C. Paxton: Conceptualization, Methodology, Software, Investigation, Validation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Project administration. Ryan Daley: Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization. David P. Forrestal: Resources, Methodology, Writing - original draft, Writing - review & editing, Project administration. Mark C. Allenby: Resources, Writing - review & editing, Project administration, Funding acquisition. Maria A. Woodruff: Resources, Writing - review & editing, Project administration, Funding acquisition.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.matdes.2020.108787.

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