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Electrospinning writing with molten poly (ε-caprolactone) from different directions – Examining the effects of gravity

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A B S T R A C T

This work investigates the effect of gravity during melt electrospinning writing (MEW) and explores the feasibility of developing MEW devices with lateral and upside down print head configurations. Average fibre diameters of printed constructs using different printing directions and their variability reveal particular differences. These give an insight into the effect of gravity, which was observed to affect the Taylor cone, yet interestingly not the fibre jet. Additionally, stable processing conditions were studied and showed that it is possible to reproducibly print from all directions using MEW.

1. Introduction

Products with high surface-to-volume ratios have contributed to various applications across diverse industries [1,2], most recently to the fields of tissue engineering and regenerative medicine (TE&RM). An electrohydrodynamic process – defined in the literature as electrospinning – can generate micron- to submicron-scale fibres from viscous polymers (dissolved in a solution or molten) when in close proximity to an electrical field. In both solution and melt electrospinning (SE and ME, respectively), the interaction of the prevailing system parameters (Fig. 1A) leads to the establishment of a Taylor Cone on the tip of a spinneret (Fig. 1B). Its conical shape resembles an equilibrium between pressure-induced mass flow into the Taylor cone and forces pulling material out of the cone arising from electrostatic, gravitational and mechanical drag forces (Fig. 1C) [3–5].

The disparity in viscosity between molten polymers and polymers dissolved in solvents leads to significant differences in both mass flow and fibre diameters, with the former producing diameters typically two orders of magnitude larger due to the significantly larger mass flows. As the mass flow in the SE process is very small, the effect of gravity during the spinning process is suggested to be negligible [6]. This fact enabled the design of SE machines for multidirectional printing, broadening industrial applications. Significantly larger mass flows occurs during ME, indicating that the influence of gravitational forces may have an effect on the process. However, there is a lack of research directed to address the effect of gravity, especially in ME Writing (MEW). To our knowledge, MEW is conducted exclusively from a top-down orientation and, although in rare cases gravity is included as a parameter in computational modelling of the process [7], its effect on the fibre itself, compared to the arising electrostatic forces, is routinely ignored [8]. One recent study describes a common unstable behaviour of the Taylor cone during MEW, termed fibre pulsing [9]. Viscoelastic forces hold the melt together but in the case of an imbalanced mass flow, material aggregates within the Taylor cone until a large material excess is released towards the collector in the shape of an extended bead. Fibre pulsing compromises the quality

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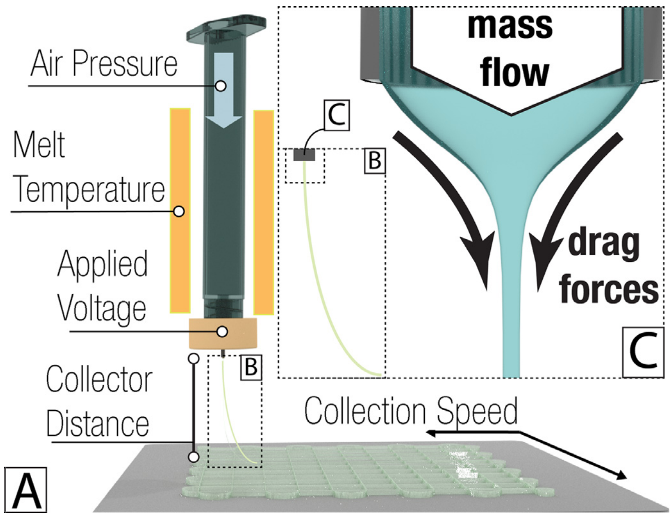


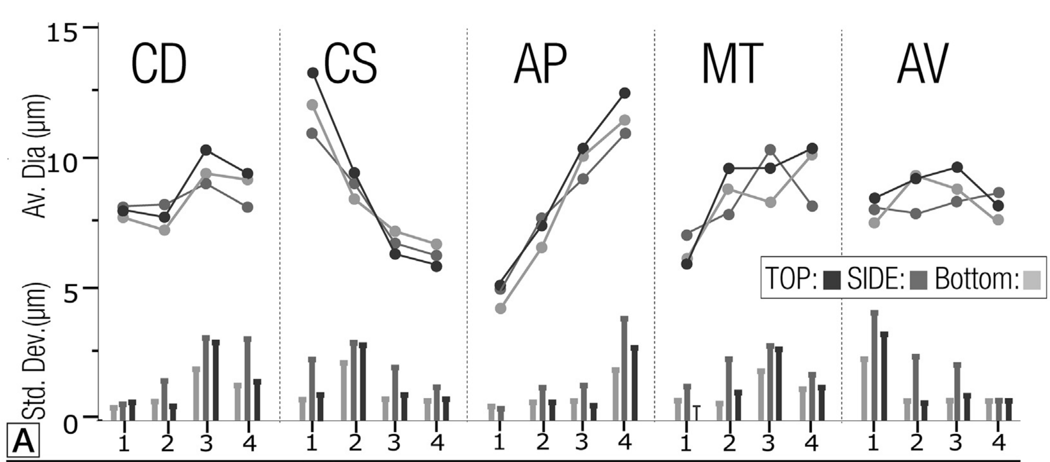
Fig. 1. A) Schematic of a typical setup for a MEW process including the parameters applied pressure (AP), melt temperature (MT), applied voltage (AV), collector distance (CD) and collection speed (CS). B) Shows the fibre flight path and C) a sectional view of a Taylor cone with schematically represented mass flow and drag forces on the extruded polymer.

and thus MEW parameters need to be optimised to ensure balanced mass flow rates. Interestingly, the authors explained the drag forces acting on the Taylor cone exclusively in terms of a combination of mechanical and electrostatic forces, yet momentarily discounted the impact of gravitational forces. Here we hypothesise that gravitational forces influence the MEW process and therefore investigate the effect of printing direction (top, side and upside down) on the quality and reproducibly of the process and product. Our final aim is to explore the vision of developing MEW devices with a vertical configuration as an alternative to the standard horizontal printing to widen the manufacturing potential of this technology.

2. Materials and methods

Medical grade poly(ε-caprolactone) (PCL Purasorb PC 12, Purac Biomaterials, Netherlands) was processed on a in-house built MEW device [10]. The influence, intensity and inter-correlation of the system parameters that control the printing process were analysed conducting a multifactorial orthogonal design study (Table 1A) [11], a methodology well-known within the electrospinning community [12,13]. It was applied to the five main system parameters that control MEW (Table 1B), i.e. collector distance (CD), collection speed (CS), applied pressure (AP), melting temperature (MT) and applied voltage (AV), and resulted in sixteen different parameter configurations, individually conducted at each print orientation. A schematic analysis helped to identify parameter hierarchies by calculating the R value (Table 1C). Scanning Electron Microscope (Hitachi, TM3000, Japan) images were used to quantify the diameters (n = 24/scaffold). The image-processing software (ImageJ; National Institute of Health, USA) was applied to measure average fibre diameters and their standard deviations using GraphPad (GraphPad v6.05, Software, Inc., USA).

Table 1
A) Results of the applied design of experiments showing the five parameters regarding diameter and standard deviation, B) their factors, levels and applied values and C) the results from the analysis which reveals the intensity of influence (R) and the order of importance (OoI).



B *Factors (Levels (1|2|3|4))*

CD	(6 I 8 I 10 I 12) [cm]
CS	(720 I 1470 I 2250 I 3000) [mm/min]
AP	(0.5 I 1.25 I 2 I 2.75) [bar]
MT	(76 I 83 I 89 I 96) [°C]
AV	(8 I 9 I 10 I 11) [kV]

C

		Av. Diameter CD	CS	AP	MT	AV	Std. Deviation CD	CS	AP	MT	AV
TOP:	R	2.89	6.86	7.16	4.11	1.31	2.50	2.07	3.33	2.30	2.70
	OoI	AP > CS > MT > CD > AV					AP > AV > CD > MT > CS				
SIDE:	R	0.93	4.49	6.48	3.20	0.62	2.66	1.73	4.50	1.64	3.43
	OoI	AP > CS > MT > CD > AV					AP > AV > CD > CS > MT				
Bottom:	R	2.73	5.30	7.13	3.84	1.67	1.53	1.50	1.70	1.31	1.62
	OoI	AP > CS > MT > CD > AV					AP > AV > CD > CS > MT				