Nanofibrous meshes by advanced electrospinning

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A novel process incorporating twin screw extrusion and electrospinning permits in-line polymer processing and inclusion of nanoparticles for structurally and compositionally complex fiber meshes.

Electrospinning polymeric resins is a versatile process used to generate experimental quantities of fibers.[1,2] Conventionally, as practiced with little change since the early 1930s,[1] the process involves placing a polymeric solution into a cylindrical reservoir and forcing it to move through a needle attached to an electrical potential source, with the resulting fibers collected on a grounded surface: see Figure 1(a). The force arising from the electrical potential overcomes the liquid's surface tension to form a 'Taylor cone' and draw out the solution as it leaves the nozzle.[1,2] A 'whipping' unstable motion is typically generated downstream to further reduce the diameter, possibly into the nano regime, as the solution travels towards the collecting surface, which can be a stationary plate or a rotating mandrel (spindle) to preferentially orient the fibers.

Although more than eight decades have elapsed since its first use, the conventional electrospinning process has not been upgraded to include further basic polymer processing capabilities, such as mixing, devolatilization, and stripping.[3] In addition, in the conventional process, incorporating particles/nanoparticles into fibers is also difficult. Particles need to be mixed with polymer solution prior to processing, but there are no facilities to prevent the reagglomeration or sedimentation of the particles during the relatively slow electrospinning process. Furthermore, there is no way to change material properties without interrupting the process. However, an extruder system that could simultaneously feed multiple ingredients in a time-controlled manner would enable polymer processing capabilities, facilitate the incorporation and dispersion of nanoparticles and other additives, and allow us to fabricate meshes that are graded over their volumes in terms of porosity, pore size, fiber diameter, and additive concentrations.[4–8] Adding a twin screw extruder as the front-end to this electrospinning process is a forward-looking approach,[9–13] and such a hybrid system can offer novel capabilities: see Table 1 for a comparison of conventional electrospinning versus twin-screw extruder electrospinning (TSEE).[4–8]
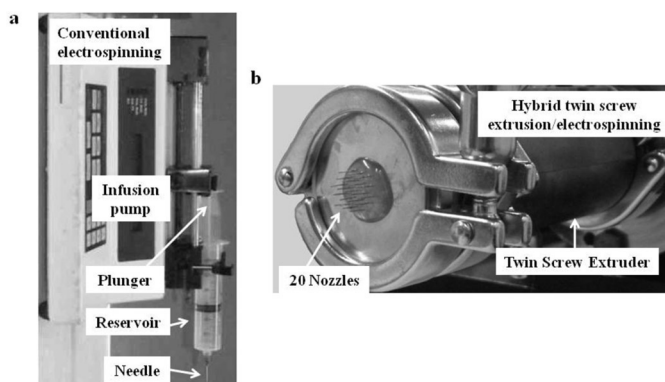

Figure 1. *(a) Conventional electrospinning process. (b) The hybrid twin screw extrusion and electrospinning process.*[8]

Such capabilities, for example, allow for the fabrication of meshes that can be used as tissue engineering scaffolds[4–7] because they can be tailored to mimic the structural and compositional characteristics of the extracellular matrices of soft as well as hard tissues. As such, the fibrous network can mimic the collagen protein present in cartilage, ligament, tendon, and bone tissues. It is known that collagen fibers in articular cartilage tissue are aligned horizontally at the surface, perpendicular to the tidemark at the cartilage-bone interface, and randomly oriented in the middle zone. In ligaments and tendons, collagen fibers/fibrils are aligned longitudinally. Control over the degree of orientation of fibers in the meshes broadens the field of application. In addition, at the cartilage–bone and tendon–bone interface, the concentration of calcium phosphate mineral particles varies monotonically in the direction normal to the axis of interface.[14,15] Therefore, TSEE technology offers new approaches for fabricating functional scaffolds for regenerative medicine.

Our hybrid process consists of a specially designed and fabricated twin screw extruder with fully intermeshing and co-rotating twin screws of 7.5mm diameter (Material Processing & Research Inc., Hackensack, NJ) and a spinneret die with three to twenty nozzles (see Figure 2). For one demonstration study, we investigated the effects of processing conditions on the orientation, diameter, and tensile properties of poly(caprolactone) (PCL) fibers. Analysis of the

Taylor cone identified that the critical voltage necessary to overcome the surface tension of the droplet was 12–14kV for our TSEE processing conditions.[8] Based on this, we found that applied voltages of 10kV or greater could generate multiple parallel jets. A typical effect of the mandrel speed on fiber orientation is shown in Figure 3. At the low linear velocity of 0.6m/s, the fibers appear to be randomly oriented, whereas at the higher linear velocity of 4.8m/s the fibers are preferentially oriented along the machine (draw) direction. We calculated values of the Hermans orientation function, f,[8] which describes the extent to which fibers are aligned, as a function of the linear velocity at 15cm distance of separation and 15kV potential difference: see Figure 4(a). (f is zero for random orientation, and 1
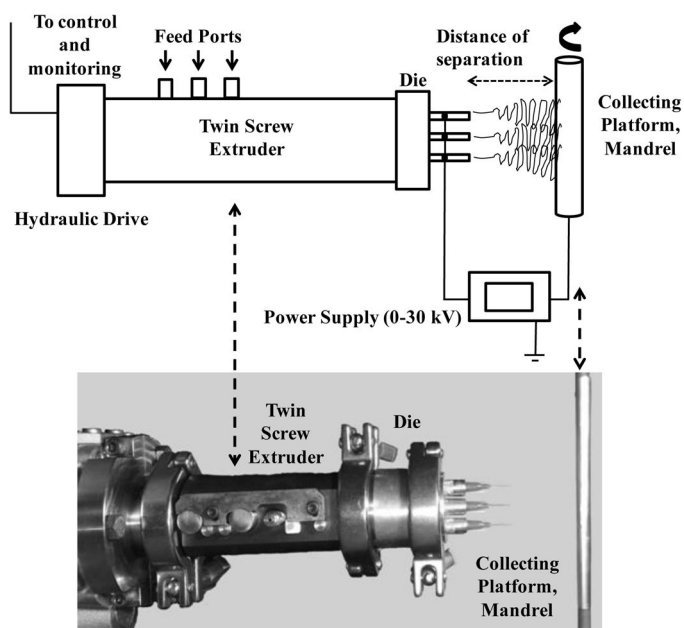

Figure 2. *The hybrid twin screw extrusion/electrospinning (TSEE) process set-up.*[8]
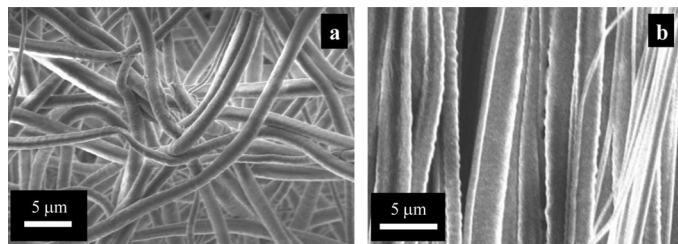

Figure 3. *Different orientation distributions. (a) At a low linear velocity of 0.6m/s, the fibers appear to be randomly oriented. (b) At a higher linear velocity of 4.8m/s, the fibers are preferentially oriented along the machine (draw) direction.*[8]
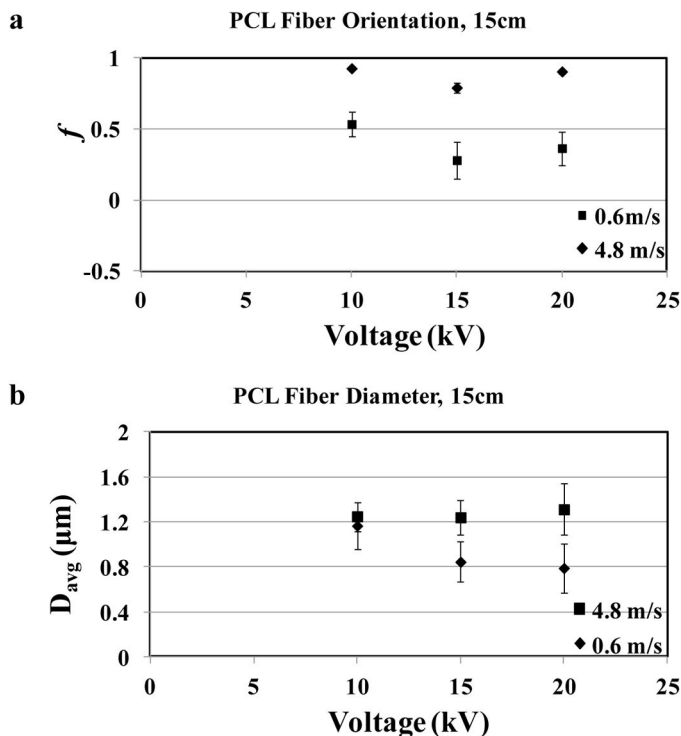

Figure 4. *(a) The Hermans orientation function, f, and (b) diameter, D_{avg}, of fibers as a function of voltage and mandrel velocity.*

Table 1. *Comparison of the capabilities of the conventional versus the TSEE process.*

	Conventional Electrospinning	TSEE
Ability to handle solid particulates	No	Yes
Melting of polymers	Possible with redesign	Yes
Mixing of ingredients	No	Yes
Pressurization/pumping	Yes but limited capacity	Yes
Devolatilization/stripping	No	Yes
Generation of graded meshes	No	Yes
Continuous processing ability	No	Yes

or −0.5 for perfect orientation of the fibers in the draw direction and in the transverse-to-machine direction, respectively.) We found that f increases from about 0.28 ± 0.13 (mean ± standard deviation) at 0.6m/s to 0.88 ± 0.02 at 7.3m/s, clearly indicating greater alignment of the fibers in the machine direction as the mandrel linear velocity increases. We also examined the effect of mandrel speed on the ultimate fiber diameter: see Figure 4(b).
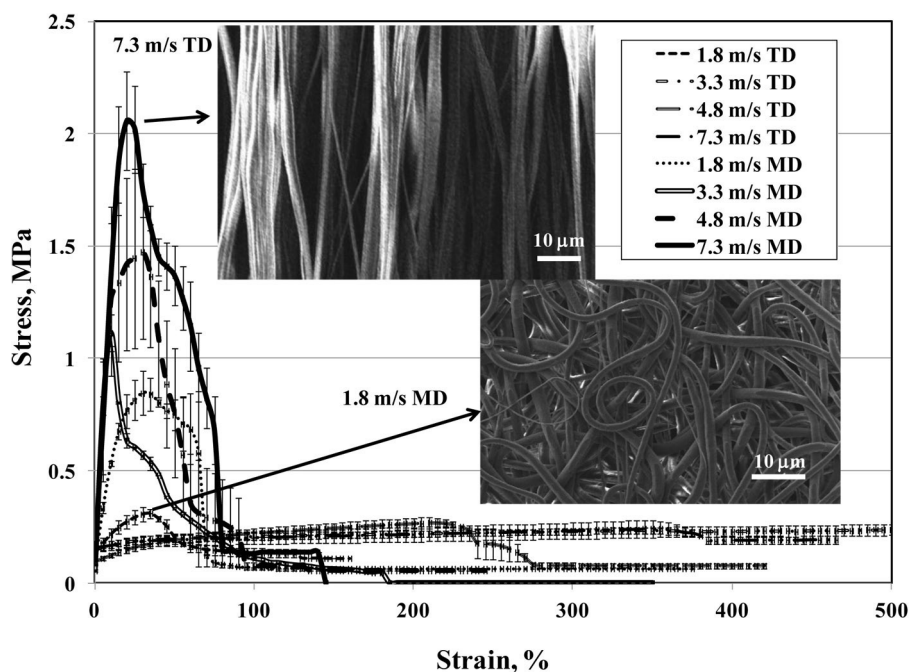
Figure 5. *Tensile properties of the electrospun fibers.[8] TD: Transverse direction. MD: Machine direction.*
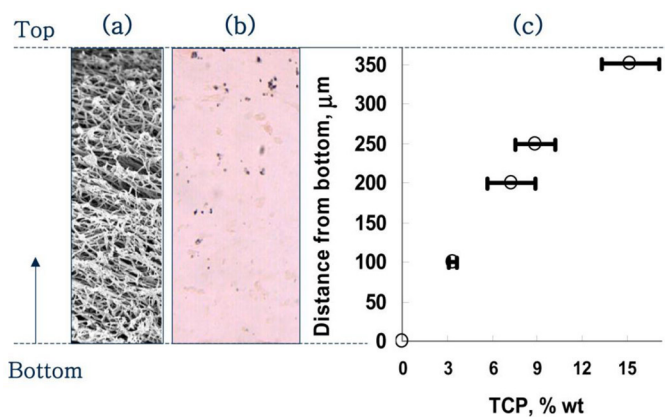

Figure 6. *Change in tricalcium phosphate (TCP) nanoparticle concentration from one side of a mesh to the other.[5] (a) Scanning electron micrograph of PCL-TCP mesh. (b) Von Kossa staining suggests that the differences in concentration of the TCP give rise to differences in mineralization upon seeding of the electrospun mesh with pre-osteoblastic cells, i.e., cells that have the capability to turn into osteoblast-type bone cells. (c) Plot of TCP concentration against position in the mesh.*

Typical tensile stress versus strain behavior shows that the samples are anisotropic with stress-at-yield, modulus, stress-at-break, and toughness (area under the stress versus strain curve) values being greater for samples cut in the machine direction than those cut in the transverse direction (see Figure 5). This is clearly a consequence of the fiber alignment. A lower degree of alignment means that under a uniaxial force, the fibers initially align before any actual deformation of them begins.

The TSEE process also allowed us to generate controlled structural and compositional gradients over the volume of the mesh. We tailored the concentration distribution of tricalcium phosphate (TCP) nanoparticles in PCL to increase from one side of the electrospun mesh to the other (see Figure 6).[4,5] Such a grading can give rise to systematic changes in physical properties of mesh such as those demonstrated here, as well as biological properties if such meshes are enriched with bioactive molecules and are used as scaffolding materials for cell proliferation and differentiation.[5–7] In one of our applications, concentration gradients of insulin, a stimulator for chondrogenic differentiation (conversion of stem cells into cartilage cells), and beta-glycerophosphate (beta-GP), a stimulator for mineralization, were generated along a PCL mesh. The mesh was seeded with human stem cells and cultured over eight weeks. The resulting tissue constructs revealed indications of selective differentiation of stem cells toward chondrogenic lineage (cartilage-like tissue formation) and mineralization (bone tissue formation) as functions of position as a result of the corresponding concentrations of insulin and beta-GP6.[6] Overall, this example[6] further demonstrates the versatility of the hybrid TSEE process. This

versatility renders it a good alternative for processing complex fibrous and nanofibrous meshes with structural and compositional complexities that can be used in many fields including sensors, membranes, catalysis, and filtration applications.

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