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1 **Design and development of a nozzle-free electrospinning device for the high-throughput production of**
2 **biomaterial nanofibers**

3

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10

11 **Abstract**

12 This technical note provides a step-by-step guide for the design and construction of a temperature-
13 controlled nozzle-free electrospinning device. The equipment uses a rotating mandrel partially
14 immersed within a polymer solution to produce fibers in an upward motion by inducing the formation
15 of multiple Taylor cones and subsequently multi-jetting out of an electrified open surface. Free-surface
16 electrospinning can overcome limitations and drawbacks associated with single and multi-nozzle
17 spinneret configurations, such as low yield, limited production capacity, nonuniform electric field
18 distribution, and clogging. Most importantly, this lab-scaled high-throughput device can provide an
19 alternative economical route for needleless electrospinning research, in contrast to the high costs
20 associated with industrially available upscaling equipment. Among the device's technical specifications,
21 a key feature is a cryo-collector mandrel, capable of collecting fibers in sub-zero temperatures, which
22 can induce ultra-porous nanostructures, wider pores, and subsequent in-depth penetration of cells. A
23 multi-channel gas chamber allows the conditioning of the atmosphere, temperature, and airflow, while
24 the chamber's design averts user exposure to the high-voltage components. All the CAD files and point-
25 by-point assembly instructions, along with a list of the materials used, are provided.

26

1

2 **Highlights:**

3 A step-by-step guide for the design and development of a cost-effective, high-
4 throughput free-surface electrospinning device.

5 • The nozzle-free electrospinning device is capable of producing fibres in the
6 micro/nanoscale. Random and aligned nanofibres mats can be produced at low and
7 high revolution of collector respectively.

8 • Cryo-electrospinning is feasible through a special cylinder collector assembly, which
9 can significantly increase the pore size and porosity of the developed nanofibrous
10 scaffolds.

11 • Three variants of the spinneret assembly; a cylinder, a ball, and a spiral coil can
12 accommodate different solution volumes and large-scale production of nanofibres, as
13 the free-surface electrode has no clogging issues, and it allows the formation of
14 multiple Taylor cones throughout its surface.

15 • A multi-channel gas chamber allows the conditioning of the atmosphere, temperature,
16 and airflow, which has a direct effect in adjusting the solvent evaporation rate. The
17 design of the chamber ensures that there is no exposure of the user to the high-voltage
18 components.

19

27 **1 Introduction**

28 The unique properties presented by fibrous materials in the nano/microscale have directed the
29 advancement of several fiber-processing techniques today. Among them, including thermal-induced
30 phase separation, drawing, template synthesis, and self-assembly, electrospinning is of considerable
31 significance as a rapidly evolving fiber preparation method (1). As a highly versatile method,
32 electrospinning can process solutions, suspensions, or melts into fibers of varying diameters with low
33 standard deviation (low polydispersity) and is the only process, at present, capable of mass-producing
34 continuous nanofibers (NFs) (2, 3).

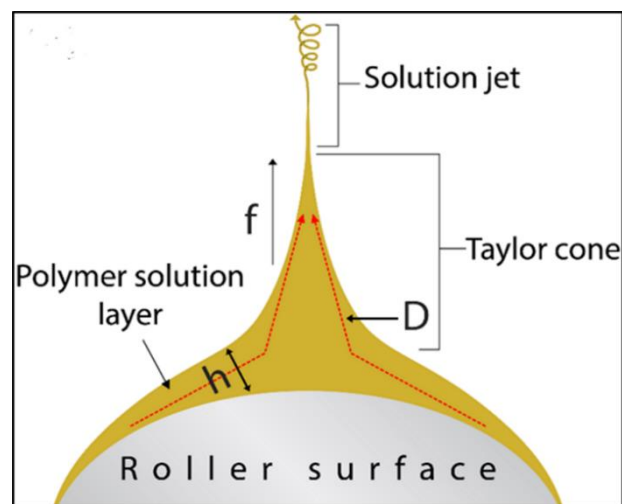
35 Electrospun NFs offer unique properties due to their high surface-to-volume ratio, fiber-length-to-
36 diameter aspect ratio, and porosity (generally $\geq 70\%$) (4). The NFs produced can be tuned to present
37 variant configurations – giving rise to unique fiber assemblies, i.e., aligned, porous, ribbon-like, hollow,
38 helical, beaded fibers, which can greatly expand the complexity and subsequent potential of such
39 biomaterials (3). As such, the structural diversity of electrospun materials have made them of
40 prominence in several subfields of biomedical engineering and, in particular, tissue engineering (5),
41 drug delivery (4), wound healing(6), and biosensing (7).

42 The electrospinning process represents an electro-fluid-dynamics problem, which stimulates
43 electrified liquid jets to whip and elongate to form fine fibers (8). A standard laboratory-scale setup
44 consists of four main components: a high-voltage DC (or AC) power supply, a syringe pump, a nozzle
45 (usually metallic capillary), and a collector that can simply be a metallic foil/plate/disc (9).

46 During conventional electrospinning, electrostatic forces accumulated, by applying a high voltage
47 to a polymer solution extruded through a nozzle-spinneret, induce a conically-shaped geometry referred
48 to as the 'Taylor cone' at the nozzle's orifice. The repulsive electric forces overcome the surface tension
49 of the polymer solution/melt, leading to vigorous whipping and splitting motions due to the bending
50 instabilities generated, enabling a jet stream of fibers to travel towards a neutral (or oppositely charged)
51 collector (10).

52 Considering that the production output of needle-based electrospinning devices is commonly
53 meager, ranging at 0.01–0.3 g/h, scaling up the process has been progressively studied as a suitable
54 approach to industrializing this fabrication process (10). Over the years, this was generally achieved by
55 scaling up the spinneret's structure while retaining an energetically stable and well-distributed
56 configuration. As opposed to multi-needle electrospinning, where the electric field around a given
57 needle is affected by the nearby jets, which can produce inhomogeneous fibers, free-surface
58 electrospinning is an alternative method capable of producing fibers at high-throughput with no
59 constraints of clogged needles (11).

60 During nozzle-free electrospinning, the polymer solution is submerged in a bath containing a
61 rotating cylinder electrode against a biased rotating collector electrode (12-14). By controlling the
62 motor, the rotating speed of the roller can be changed. High-voltage power with a potential greater than
63 40 kV needs to be applied between the two rotating electrodes, which induces the formation of multiple
64 Taylor cones emerging from the rotating electrode surface immersed in the solution bath (14, 15). When
65 voltage is applied on the roller, the liquid changes to a conical shape and forms a significant number of
66 Taylor cones (Figure 1) on the surface of the rotating spinneret. The roller electrospinning method has
67 been proven to be a continuous and efficient process to fabricate NFs.



68 **Figure 1.** A schematic diagram of an open surface electrospinning Taylor cone formation, where h is
69 the thickness of the layer, D is the diameter covered by the Taylor cone, and f is the electrostatic force

70 The concept behind free-surface electrospinning was initially described by Yarin and Zussman back
71 in 2004 (16), and the self-organization of electrified liquid jets from an open flat surface was

72 mathematically delineated by Lukas et al. in 2008 (17), to date, research surrounding needleless
73 electrospinning equipment accounts for less than 1.3% of the available literature. This could be possibly
74 attributed to the high number of patents associated with free-surface electrospinning setups, as well as
75 the extravagant costs of the commercially available equipment. For instance, products such as
76 Nanospider™ (Elmarco, Ltd., Czech Republic) (18) an industrial-scale electrospinner, where a high-
77 voltage potential (up to 80 kV) facilitates the formation of fibers out of a polymer-layered thread at a
78 defined rate, cost anywhere between 170,000 to 300,000 USD (3,18). Ultimately the prevalence of
79 conventional electrospinning prevents the clinical translation of several exciting and innovating
80 advancements in the field, which present no real-world impact.

81 Our group's previous studies reported high production rates using rotating stainless steel and copper
82 coil spinnerets. We have shown that the fiber production rate of the nozzle-free setup to that of a
83 commercially available electrospinning device (IME, Netherland) using 7.5% (w/v) polycaprolactone
84 (PCL) is an 11-fold higher (6). In a similar study, Wang et al. (19) indicated that hybrid nanoparticle-
85 decorated chitosan NFs using a cylinder spinneret produced fibers at a 50 g/h rate instead of 0.02-1 g/h
86 for the needle-based electrospinning device employed.

87 In a recent study by Agrawal and Pramanik (20), chitosan- poly(vinyl alcohol) blended nanofibrous
88 scaffolds (with an average fiber diameter of 269 nm), formed using a needleless setup, were found to
89 present good attachment, growth, and expansion in human mesenchymal stem cells. Keirouz et al. (5)
90 and (6) employed the device developed to successfully electrospun PVP/poly(glycerol sebacate) (PGS)
91 semi-transparent skin-like membranes with similar mechanical properties to anatomically variant skin
92 regions, as well as silk fibroin-containing trinary composite microfibers incorporating PCL and PGS,
93 which presented tuneable hydrophobicity. Radacsi et al. (21) utilized a similar needleless
94 electrospinning device to fabricate nanoparticle-decorated poly(vinylpyrrolidone) (PVP) and
95 polyaniline (PANI) NFs (average fiber diameter 123.9 ± 32 nm). Tan et al. (22) employed the nozzle-
96 free electrospinning apparatus to develop carbonized electrospun polyacrylonitrile (PAN)/poly(acrylic
97 acid) (PAA) for electrochemical sensing using precursor NFs containing iron oxide, gold nanoparticles,
98 or reduced graphene oxide.

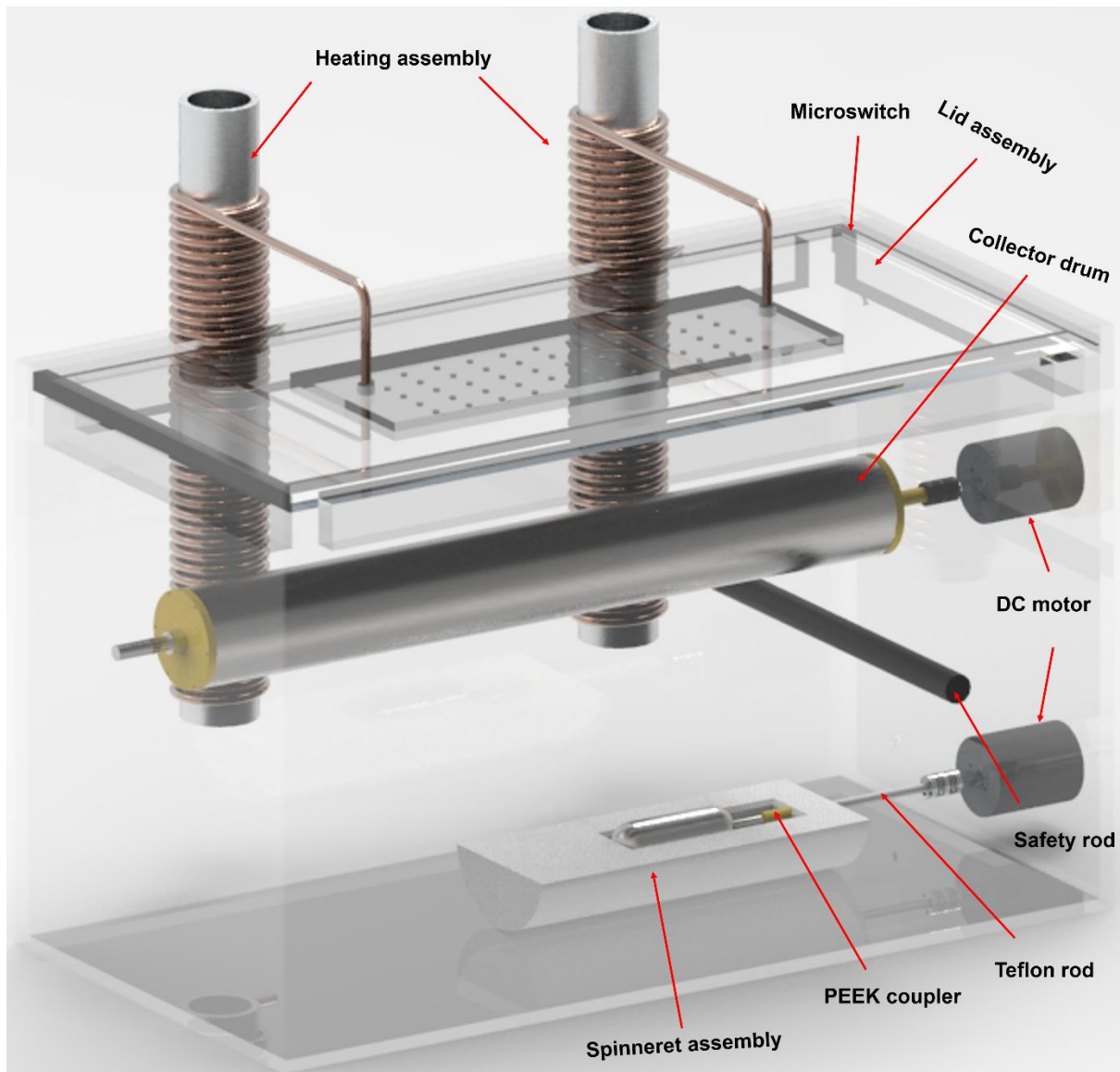
99 The technical note presented here describes the design and construction of a nozzle-free
100 electrospinning apparatus that encompasses several configurations of spinnerets, collector assemblies,
101 and solution reservoirs manufactured to optimize polymer efficient production of micro/-nanofibers.
102 The cost-effective design provided, costing between 1500-2000 USD to assemble, can permit
103 researchers to conduct lab-scaled research on high-throughput fiber production at a low cost.

104 **2 Experimental section**

105 A comprehensive list of the materials and components used to construct the nozzle-free electrospinning
106 device is provided in Table S1. All the setup parts were designed using Solid Edge (v.2019, Siemens
107 PLM Software, USA). The CAD files of the various components (in .par file format) are available for
108 download at the journal's website.

109 **3 Results and discussion**

110 A rendered CAD model of the nozzle-free electrospinning equipment is depicted in Figure 2. The setup
111 consists of five major sub-assemblies: (i) the spinneret, (ii) the collector drum, (iii) heating units, (iv) a
112 three-layer lid, and (v) electronics. An exploded CAD model of the nozzle-free electrospinning setup
113 can be found in Figure S1.



114
 115 **Figure 2.** Rendered CAD model of the nozzle-free electrospinning setup with that description of each
 116 assembly and device component

117

118 3.1 Safety measures

119 As electrospinning uses high voltage to electrify the polymer solution and produce fibers, an electrically
 120 insulating material is required as a safety precaution. As glass presents a very high dielectric strength
 121 and resistivity, a low coefficient of thermal expansion, high tensile strength, and is transparent, it was
 122 chosen for the casing (23). For the casing of the electrospinning setup, a rectangular glass tank
 123 (aquarium) of 5 mm glass thickness (dimensions: 610 (length) x 308 (width) x 380 (height) mm) was
 124 used. In total, 13 holes were carefully drilled in various compartments of the glass aquarium using a

125 circular diamond-tipped drill bit hole saw and drill positioning tools, taking into account the fragility of
126 glass material.

127 A round plastic (polyoxymethylene; POM) safety rod was placed below and antiparallel to the
128 collector's direction as a safety measure to prevent direct contact between the negative and positive high
129 voltage connections, in the unlike scenario, the collector drum was to detach during the electrospinning
130 process due to high rotation speed.

131 At the top of the glass tank, four rectangular acrylic pieces were glued on, using epoxy, facing
132 inwards and parallel to each other, to support the placement of the lid. A safety interlock was mounted
133 on one of the rectangular acrylic pieces, at the midsection between the top of the aquarium and the lid
134 support, where the interlock (microswitch) was placed, allowing for the automatic shutdown of the high
135 voltage components and prevent the onset of high voltage at the absence of the lid.

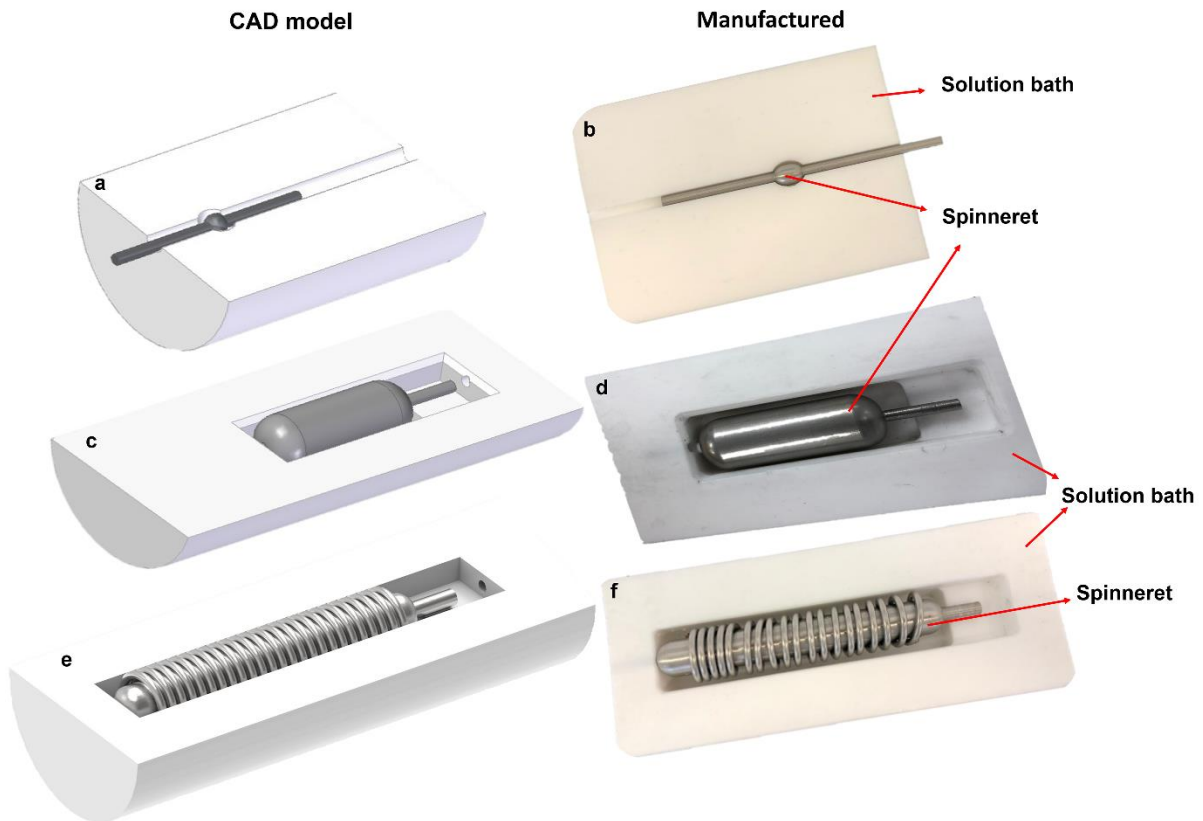
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137 **3.2 Fabrication of the spinneret assembly**

138 The spinneret configuration during free-surface electrospinning plays an imperative part towards the
139 fiber production output. The spinneret's size and geometry, along with the polymer solution properties,
140 ambient parameters, and applied voltage, will direct the number of the emerging Taylor cones from the
141 open surface. Wei et al. (24) found that the electric field intensity reaches the highest values at the ends
142 of the cylinder spinneret and decreases towards the center, which may hamper jet formation. Electric
143 field profile and intensity simulations using COMSOL have demonstrated that, although the highest
144 electric field profile is generated towards the center of an annular spinneret, the electric field intensity
145 is at least 5-fold higher at the edges.

146 In the setup, the spinneret is connected to a high voltage power supply via a high-voltage wire loop
147 and is partially immersed in a solution bath. As the spinneret slowly rotates, a thin film of the polymer
148 solution forms on the upper (open) side of the spinneret that is not immersed, allowing for the jetting
149 of fibers from multiple Taylor cones throughout its surface. There are three spinneret assemblies: a
150 cylinder, a ball, and a spiral coil described in this technical note Figure 3.

151 Selecting the appropriate material for the spinneret assembly is critical due to the corrosive nature
152 of different solvents. Teflon, stainless steel, and polyether ether ketone (PEEK) are well-documented
153 towards their resistant nature against common solvents (25). The spinneret assembly consisted of a
154 Teflon bath, a solid stainless-steel cylinder, a Teflon rod, a PEEK coupler, an HV wire loop, and a 12
155 V DC gear motor.



156
157 **Figure 3.** CAD models and corresponding photographs of the three spinneret assemblies. (a-b) CAD
158 model and photograph of the small spherical spinneret, (c-d) CAD model and photograph of the
159 medium-size spinneret, (e-f) CAD model, and a photograph of a large spinneret with the coil

160
161 The solution bath refers to the polymer reservoir within which the spinneret rotates. Three different
162 solution baths were made to accommodate different solution volumes. The solution bath was machined
163 from a Teflon rod stock to form a rectangular pot that can facilitate the electrospinning of polymer
164 solutions.

165 The small Teflon bath (2 mL solution capacity) presents a 5.1 mm diameter semi-cylinder carved
166 out along its length to facilitate the placement of the metallic rod that is used to rotate the spinneret
167 Figure 3(a-b). The reservoir of 16 mm in diameter and 8 mm in depth was carved in the shape of a semi-
168 sphere out of the Teflon material to contain the polymer solution. The 2 mL Teflon bath was able to
169 accommodate the immersion of a 10 mm stainless-steel metallic sphere, capable of rotating along its
170 axis. A 5 mm round shaft attached to the metallic sphere ensured its straight horizontal position along
171 the x-axis.

172 The medium solution bath was machined from a Teflon rod stock to form a rectangular pot that can
173 facilitate the electrospinning of a 40 mL polymer solution (solution bath dimensions: 90 mm (length) ×
174 30 mm (width) × 20 mm (depth)). A hole was drilled on the upper level of the rectangular pot to position
175 the spinneret with a step for the shaft Figure 3(c-d). Then, a 6 mm opening was drilled on the Teflon
176 bath, in which a small piece of Teflon rod mounted within the center (x-axis) of the metallic roller,
177 ensured its straight positioning and subsequent ability to rotate. On the opposite side, a 6 mm opening
178 drilled through the Teflon material allowed a 300 mm in length Teflon rod and a PEEK coupler to
179 connect the spinneret with the DC motor. The device was designed to facilitate a stainless-steel metallic
180 roller spinneret (113 mm (length) x 30 mm (width)). The metallic roller has tapered edges to prevent
181 concentrated high electric fields from forming. An exploded CAD model of medium spinneret can be
182 found in Figure S2.

183 The solution bath, within which the spinneret was submerged, provided a 5% margin on each side
184 of the spinneret to allow for its rotation and polymer coating, and a 10% margin on the coupler-rod side
185 for the positioning of the HV loop. Allowing minimal exposure of the polymer solution is an important
186 aspect of the device, which provides shelter to volatile solvents and allows consistency throughout the
187 electrospinning process.

188 The large spinneret assembly (60 mL solution capacity), conceptually similar to the 40 mL solution
189 bath, was machined from a Teflon rod stock to form a rectangular cavity with a step for the shaft. As
190 shown in Figure 3(e-f), the spinneret of the large assembly, a stainless-steel metallic roller, consisted of
191 a solid stainless-steel spindle spiral stainless-steel coil is welded around it. The stainless-steel roller's

192 total length was 185 mm, where the diameter along the spiral coil was 21 mm. The spiral coil geometry
193 can increase the number of Taylor cones forming along the spinneret's surface due to the increased
194 curvature that leads to a stronger electric field than the smooth spinneret used in the medium Teflon
195 bath. An exploded CAD model of a large spinneret can be found in Figure S3.

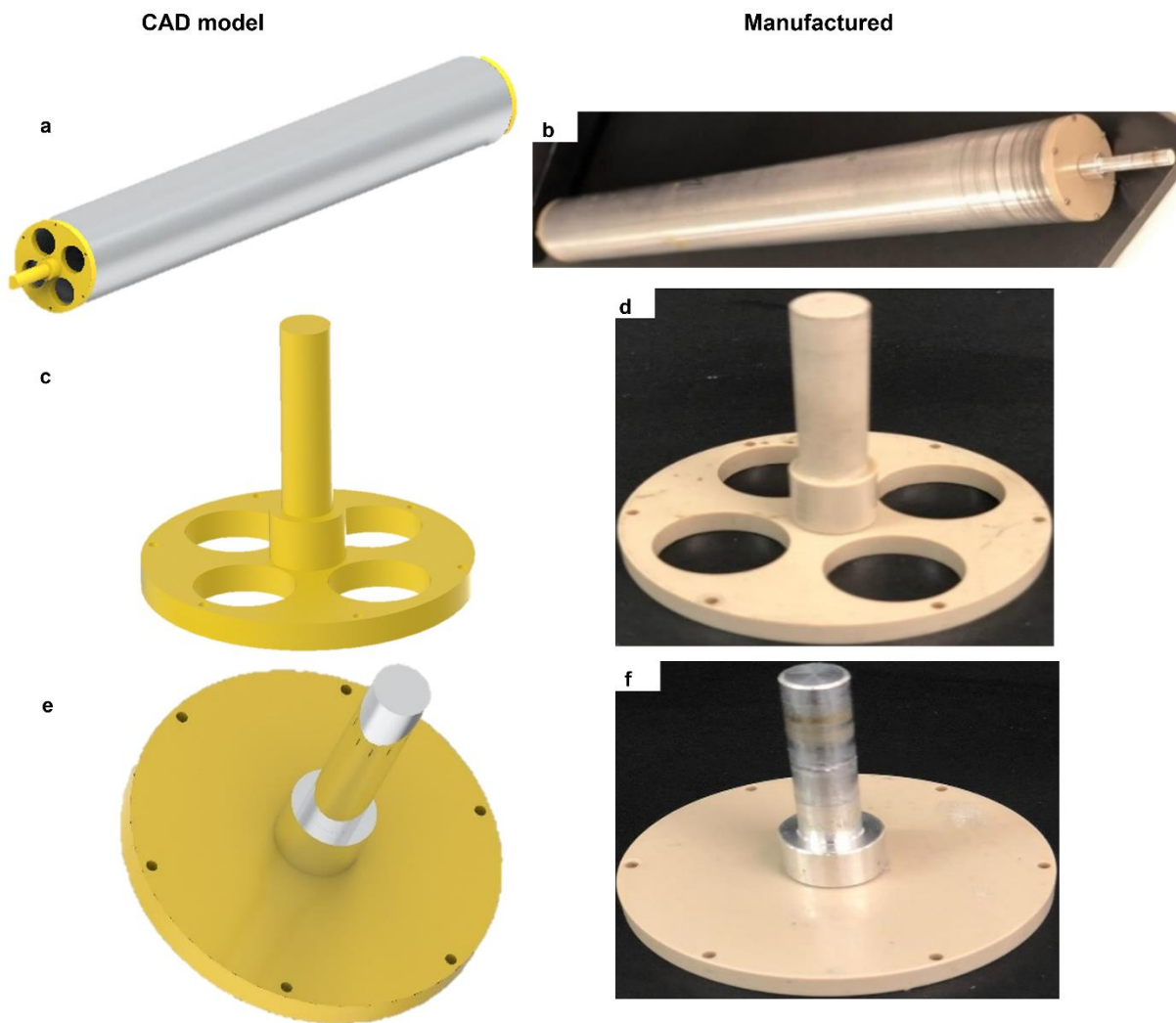
196

197 **3.3 Fabrication of the collector assembly**

198 The collector was manufactured from a stainless-steel cylinder to attain good electrical conductivity
199 and charge distribution along its surface (15). The collector assembly consisted of five distinct parts: a
200 hollow stainless-steel cylinder, two PEEK discs for the positioning of the cylinder, and two protruding
201 shafts. Four 20 mm holes on the side of the collector allowed for the insertion of dry ice. The PEEK
202 discs were fixed on the hollow cylinder by six stainless steel screws, while the shafts were mounted on
203 the discs using two stainless steel screws for each Figure S4.

204 Cryogenic electrospinning is a technique that uses a sub-zero (in °C) temperature collector to
205 facilitate the simultaneous formation of nanofibers and ice crystals. The scaffold's pore size can be
206 adjusted from 10–500 μm , depending on various controllable factors, such as size and the amount of
207 ice crystals. The ice crystals are then removed by freeze-drying the fibrous scaffolds, leaving large void
208 spaces, which create an ultra-porous biomaterial with wide pores that can permit cell infiltration (10).

209 The cryo-collector assembly has a diameter of 64 mm and is 500 mm long Figure (4a-b). The shaft
210 connecting the collector to the electric motor was made out of PEEK Figure (4c-d) to avoid electrical
211 charges escaping from the collector's surface towards the DC motor. On the opposite side, an aluminum
212 shaft Figure 4(e-f) was inserted in the center of a 10 mm-diameter metallic ball bearing, allowing its
213 rotation.



215

216 **Figure 4.** CAD model of the cryo-collector assembly (a-b) CAD model and photograph of the
 217 manufactured cryo-collector assembly (c-d) CAD model and photograph of the PEEK disc with four
 218 holes with the PEEK shaft (e-f) CAD model and photograph of the closing PEEK disc and aluminum
 219 shaft.

220

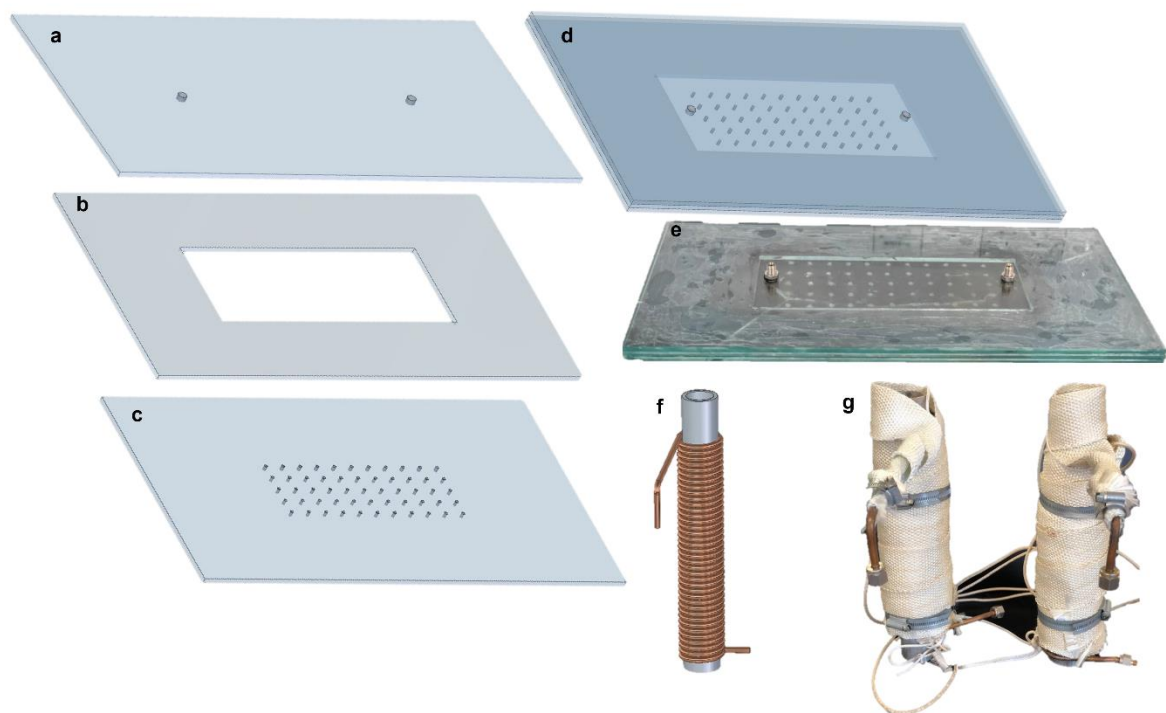
221 3.4 Heating and lid assembly

222 The lid assembly consisted of three rectangular glass plates, as shown in Figure 5(a-e). The ambient
 223 humidity is a critical factor that can directly affect the electrospinnability of a polymer solution, as well
 224 as the subsequent morphology of the fibers. For instance, high humidity can affect the morphology of
 225 the fibers by forming defects (e.g., beads), secondary morphologies (e.g., net-like spider webs), or by

226 completely halting a solution from being electrospun. The layered glass assembly allows the uniform
227 distribution of gas (hot air, nitrogen) onto the collector assembly, controlling the humidity and
228 temperature within the electrospinning chamber. Each rectangular glass plate was 590 mm (length) x
229 295 mm (width) x 5 mm (thickness). The outermost glass layer had 55 holes of 3 mm diameter arranged
230 at five rows and 11 columns, similar to a perforated glass. This allowed for the uniform distribution of
231 air/nitrogen across the glass aquarium, at a constant flow across the holes. A rectangular glass piece
232 was cut out from the middle glass plane at the same position where the 55 holes were presented on the
233 bottom glass plane to allow for the gas distribution and circulation. The top glass plane presented two
234 openings for Swagelok tube fittings from where copper tubing linked to the gas supply was connected
235 to the lid. Heavy-duty suction cups were positioned to lift the lid.

236 Controlling the electrospinning chamber temperature, by heating the gas was achieved by using two
237 heating assemblies positioned outside the glass aquarium. The heating assembly consisted of a heat
238 sink, made of an aluminum pipe (50 mm (inner pipe diameter) x 400 mm (length)). Then, 6 mm copper
239 tubing was used to wrap the heat sink, as shown in Figure 5(f). Wrapping the aluminum pipes using
240 high-temperature heating and insulation tapes, prevent heat loss to the environment. Two metallic hose
241 clamps were used to stabilize the assembly and hold it together, as shown in Figure 5(g). The high-
242 temperature insulating tapes were heated by an MC 242 electric heating controller.

243



244
 245 **Figure 5.** CAD model of the glass lid and heating assembly. (a) CAD model of top glass plane, (b)
 246 CAD model of middle glass plane with the rectangular cutout (c) CAD model of bottom glass plane
 247 with 55 holes, (d) CAD model and (e) photograph of complete 3-layer lid assembly, (f) CAD model of
 248 the heat sink with the copper coil wrapper around it (g) photograph of heating assembly

249

250 **3.5 Electronics**

251 Two high-voltage DC power supplies (Information Unlimited, New Hampshire, USA) of adjustable
 252 output voltage, one of negative and one of positive voltage output, were utilized to electrify the polymer
 253 solution and draw the fibers towards the collector. Both have the capability to be adjusted between
 254 5-35 kV, allowing the users to set a total potential difference of up to 70 kV between the rotating
 255 collector and the spinneret.

256 The rotations of the spinneret and the collector are independently controlled by DC motors. The
 257 spinneret rotational speed is constant, controlled by a direct current, 6 V at 5 revolutions per minute
 258 (rpm) when no load is coupled to the shaft. The collector is fitted with a brushed DC motor rated at

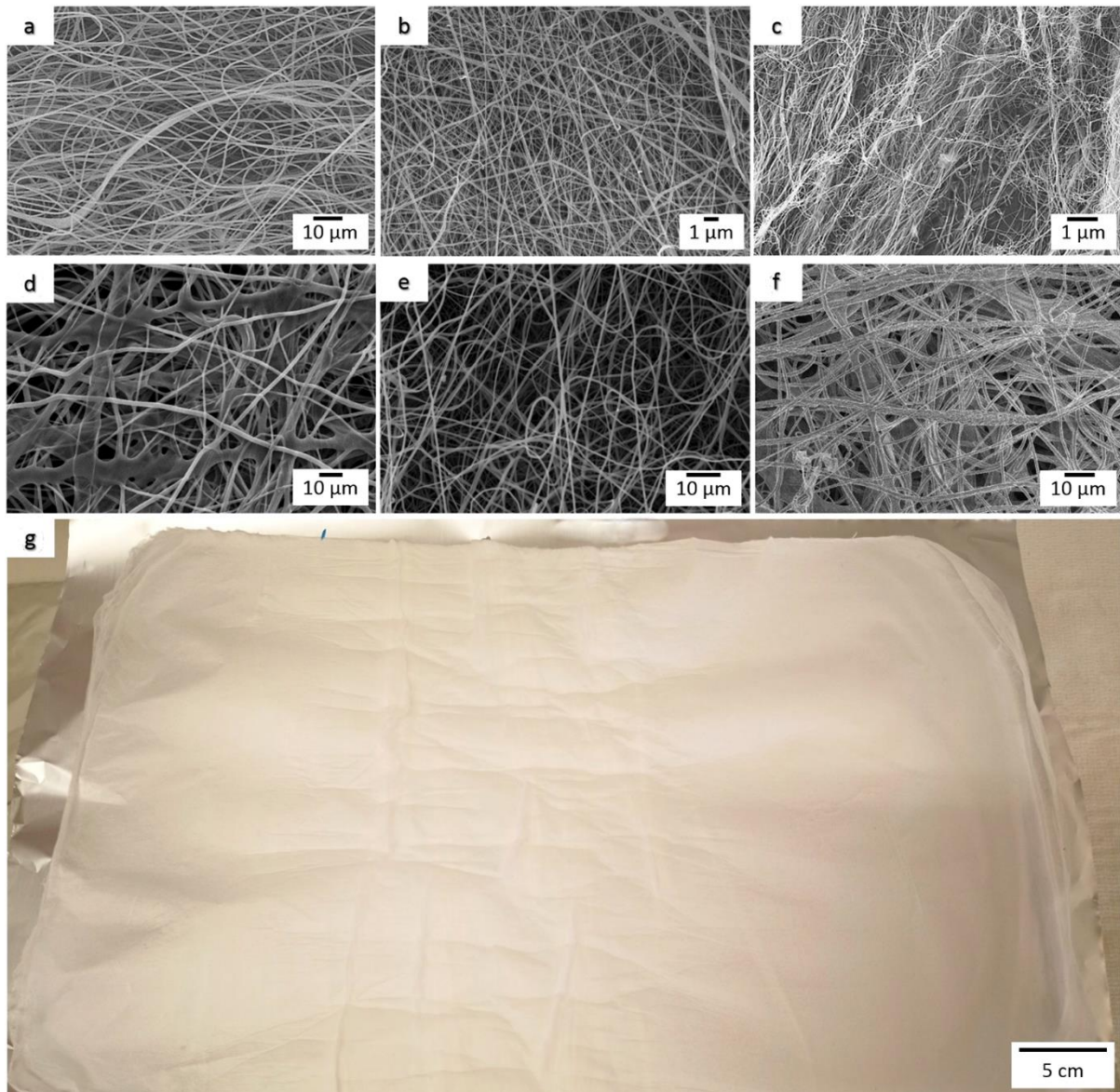
259 4500 rpm when unloaded (Bosch, Germany). The user can adjust the effective rpm utilizing two
260 controlling mechanisms; a speed controller and a DC source feeding the circuit.

261 The speed controller module used with the proposed setup (Model EM-185, Electromen OY,
262 Finland) regulates the effective voltage fed to the motor, enabling the user to set the rotation of the
263 collector from an estimate of 100 rpm up to its rated maximum rpm value, when no load limitation due
264 to weight is considered. This controller supports only coarse rpm adjustments and will not allow the
265 user to reliably set speeds below 100 rpm. The module can be powered up by any DC source that
266 provides 12-24 V DC, and it can safely source up to 3 A to the motor. Identifying the maximum current
267 that the module can handle is important for the design since the setup is required to operate under heavy
268 load conditions when the hollow collector is filled with dry ice in the cryo-electrospinning mode. In
269 this case, a higher current spike is required by the motor for initiating rotation, which can be easily
270 covered by the 3A limit outlined for the selected speed controller.

271 The power source selected for powering up the collector motor and its control circuit is an adjustable
272 DC power supply (Model HCS 3102, Manson Engineering Industrial Ltd.) with programmable output
273 voltage and current. The user can select an output voltage between 0 and 30 V in 0.1 V increments and
274 an output current between 0 and 5 A with 0.1 A increments. The selected source supports constant
275 current and constant voltage supply modes. Users will typically employ the constant voltage supply
276 mode, which will provide the requested voltage to the load while keeping it constant but allows
277 variations in the supplied current.

278 **3.6 Fabrication of nanofibers**

279 The current nozzle-free electrospinning setup was successfully used to produce NFs using different
280 polymers. The SEM images of these electrospun NFs are shown in Figure 6 (a-f). The nozzle-free
281 electrospinning setup can produce homogenous and uniform electrospun mats over a large area. The
282 higher production rate of electrospun fibers can be achieved in very short time, 1.45 g of nanofibers
283 collected on an aluminum foil in just 18 minutes, as shown in Figure 6 (g).



284

285 **Figure 6.** Nozzle-free electrospinning setup used to produce electrospun fibers using different polymers
 286 (a) Polyvinylpyrrolidone in N, dimethylformamide (DMF)/Ethanol/distilled water (b) polycaprolactone
 287 in trifluoroacetic acid (c) silk fibroin dissolved in trifluoroethylene (d) polyaniline / polyacrylic acid
 288 in DMF (e) polyacrylonitrile in DMF (f) polyvinylidene fluoride/polyethylene glycol in DMF/distilled
 289 water (g) polyvinylidene fluoride/polyethylene glycol composite material electrospun directly on an
 290 aluminum foil. The electrospun mat shown in Figure 6(g) was obtained within 18 minutes of
 291 electrospinning

292 **4 Conclusion**

293 Nozzle-free electrospinning is a promising technology for large-scale production of NFs, as free-surface
294 electrodes are not associated with clogging issues and nonuniform electric field distribution, allowing
295 for the formation of multiple Taylor cones across the spinneret's surface. This technical note presents a
296 step-by-step guide for the fabrication of a low-cost, temperature-controlled, nozzle-free electrospinning
297 setup. The setup includes a cryo-collector, which enables cryo-electrospinning for obtaining ultra-
298 porous materials. Three different spinnerets of variable size and geometries allow different solution
299 volumes to be accommodated. A multi-channel gas lid allows uniform gas circulation, counter to the
300 electrospinning direction, capable of controlling the humidity and temperature, which directly affects
301 the solvent evaporation rate. As indicated, this setup has been successfully tested using several polymers
302 and solvent systems and can be further validated by published works in the fields of drug formulation
303 (4), tissue engineering (5), and wound healing (6). By utilizing this setup, high-throughput production
304 of fibers can be achieved efficiently and at a low cost that can benefit the advancement of electrospun
305 materials in health care, energy, and a wide range of industrial sectors.

306

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310 input to improve the image quality.

311

312 **Conflict of interest**

313 None.

314

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319 support.

320

321 **Availability of supporting data**

322 Table S1 provides information and the suppliers for all the materials used to assemble the nozzle-free
323 electrospinning device. The CAD and part files (.Par file format) can be downloaded at no cost.

324

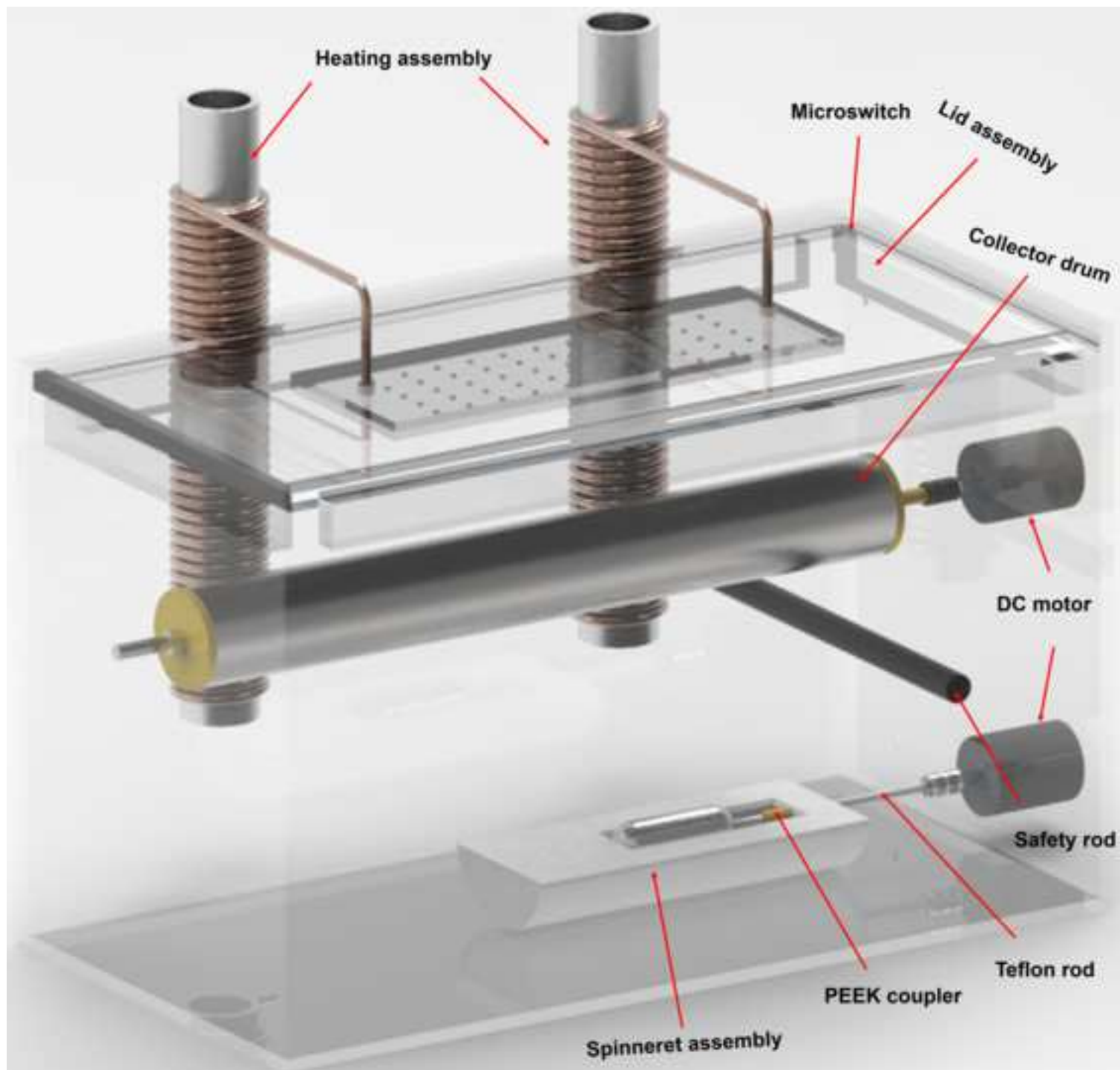
325 **Ethical Approval:** Not required

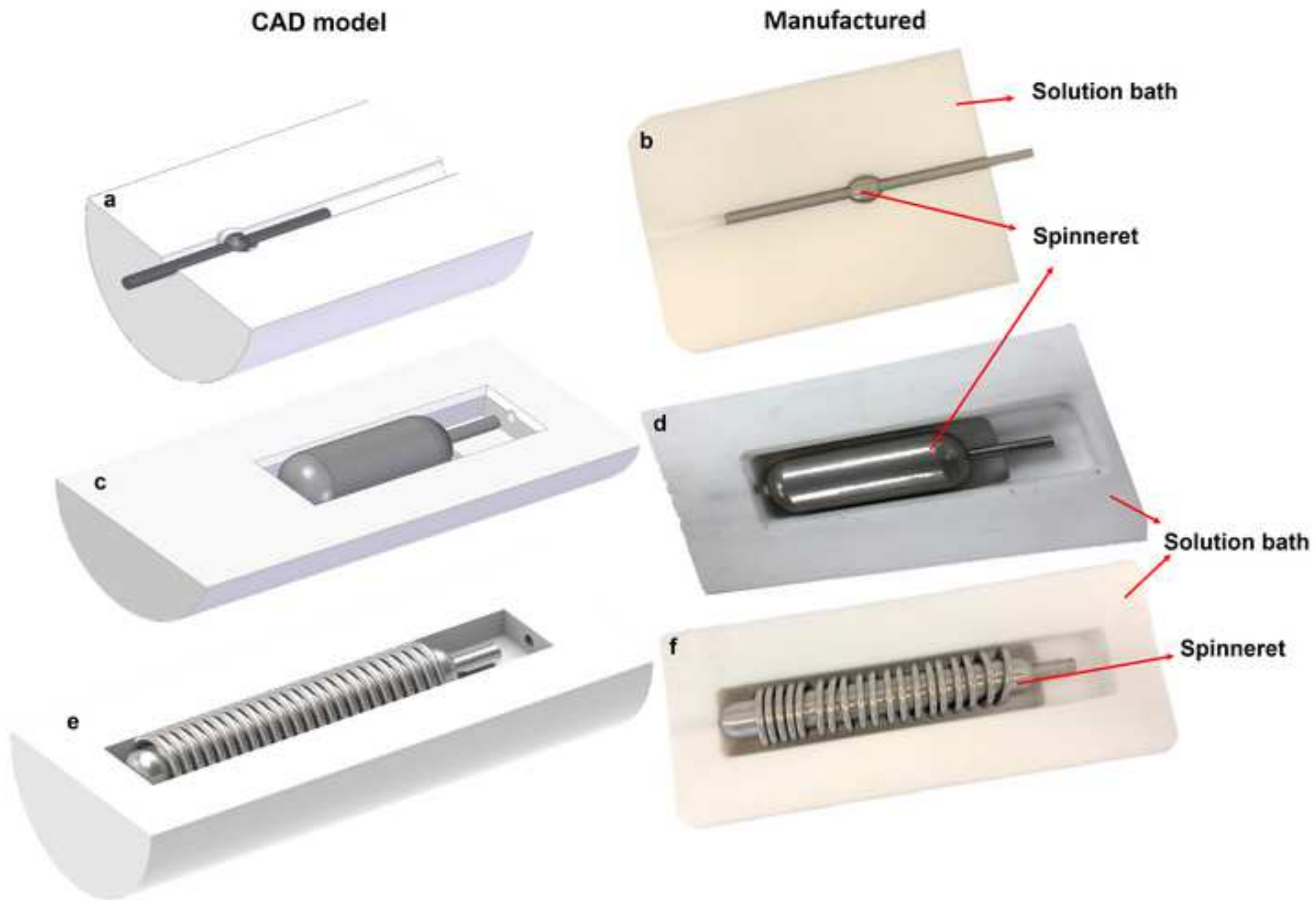
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CAD model



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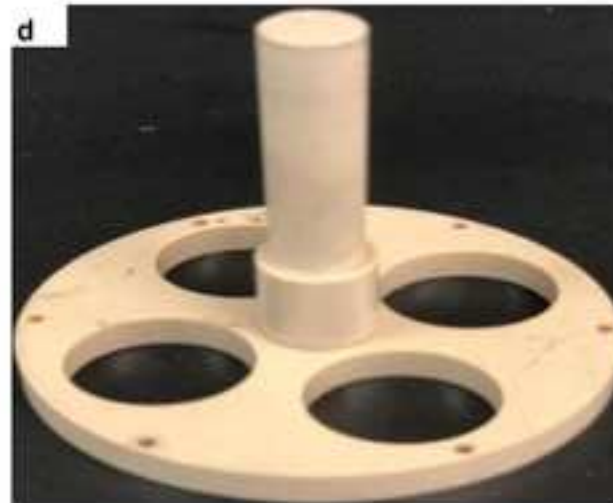
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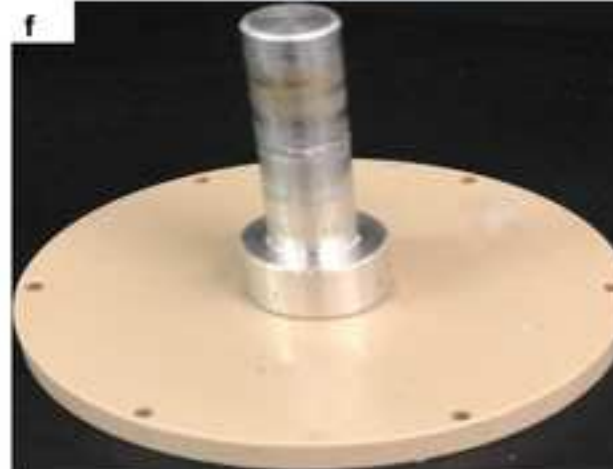
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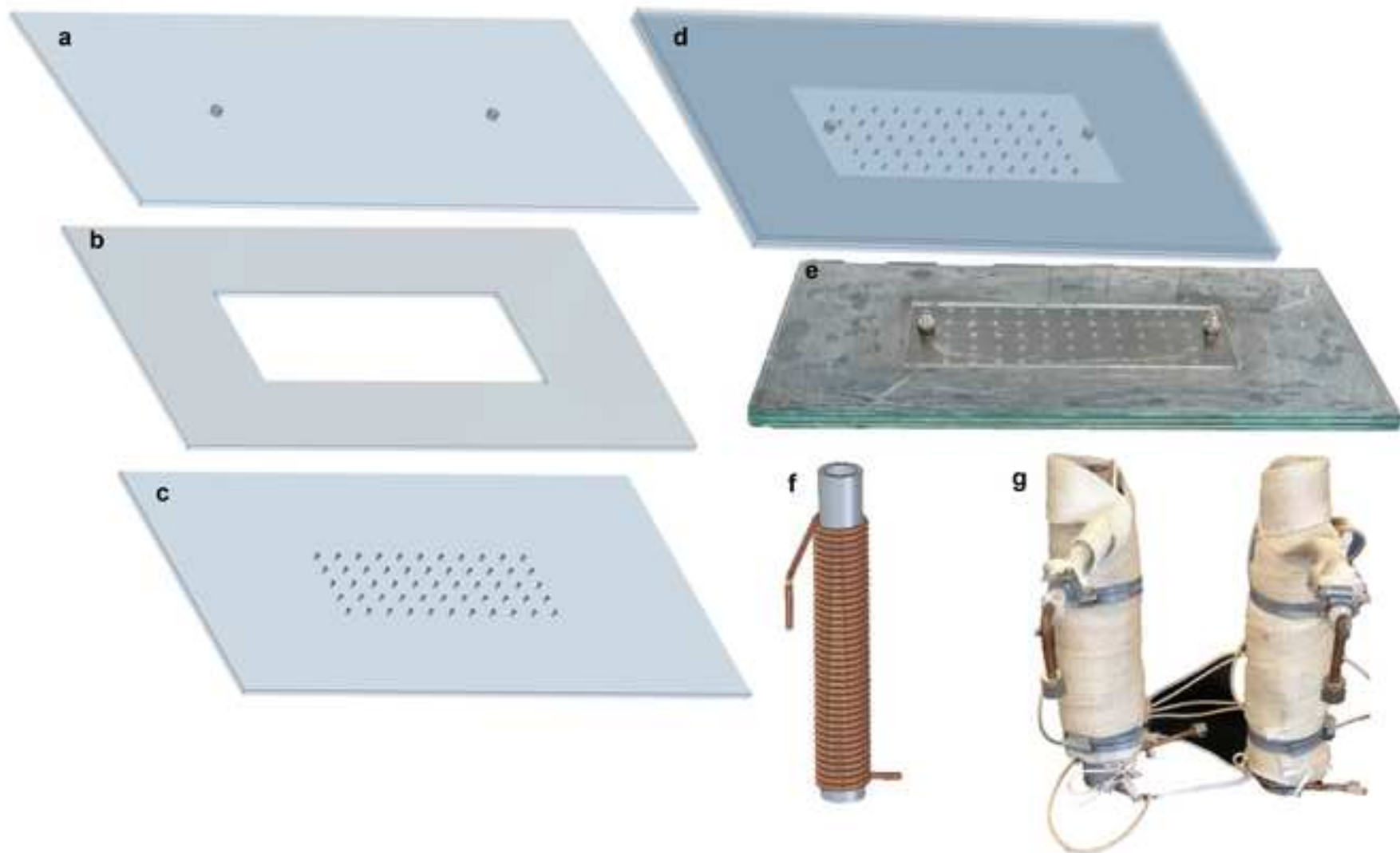


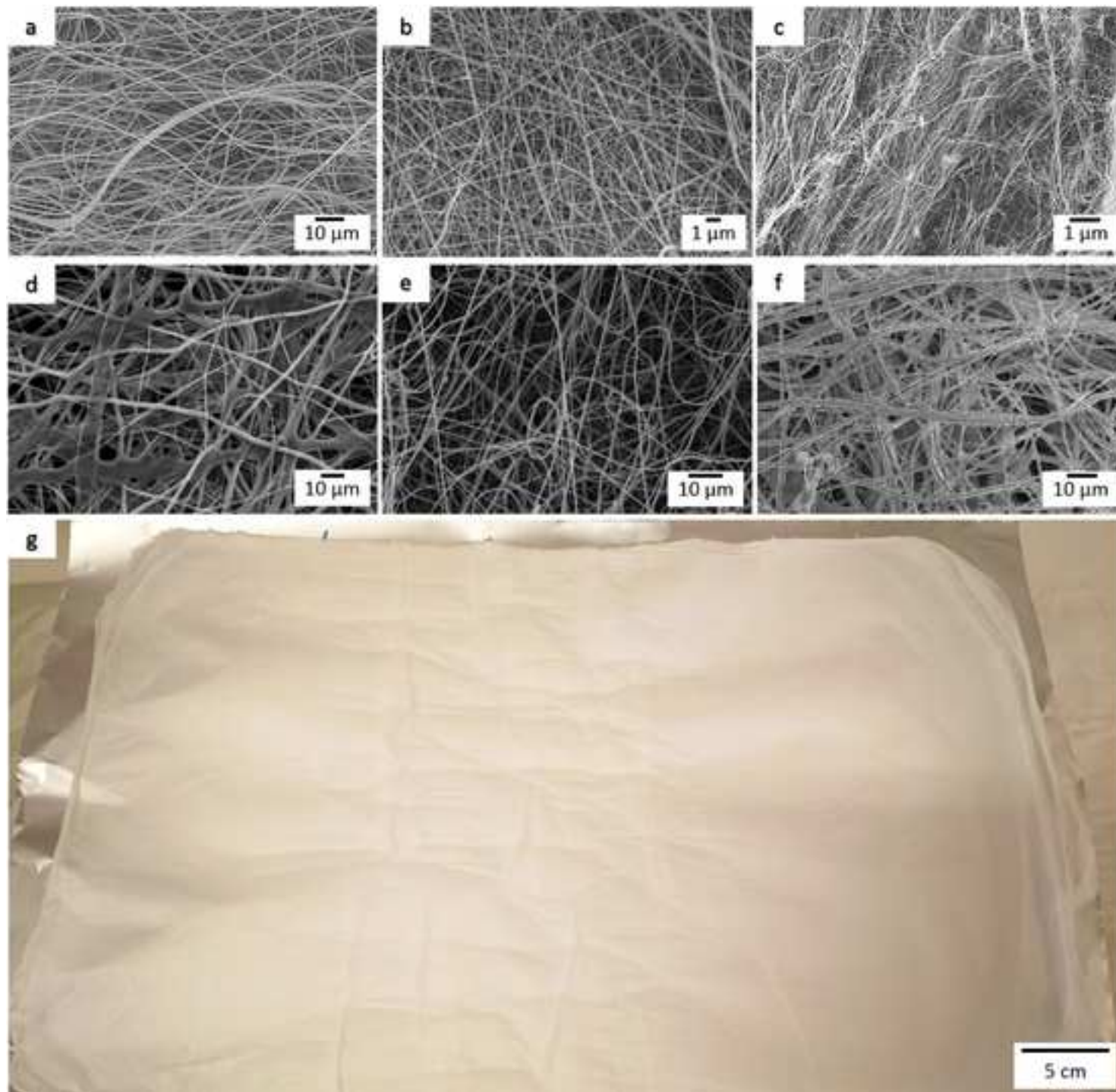
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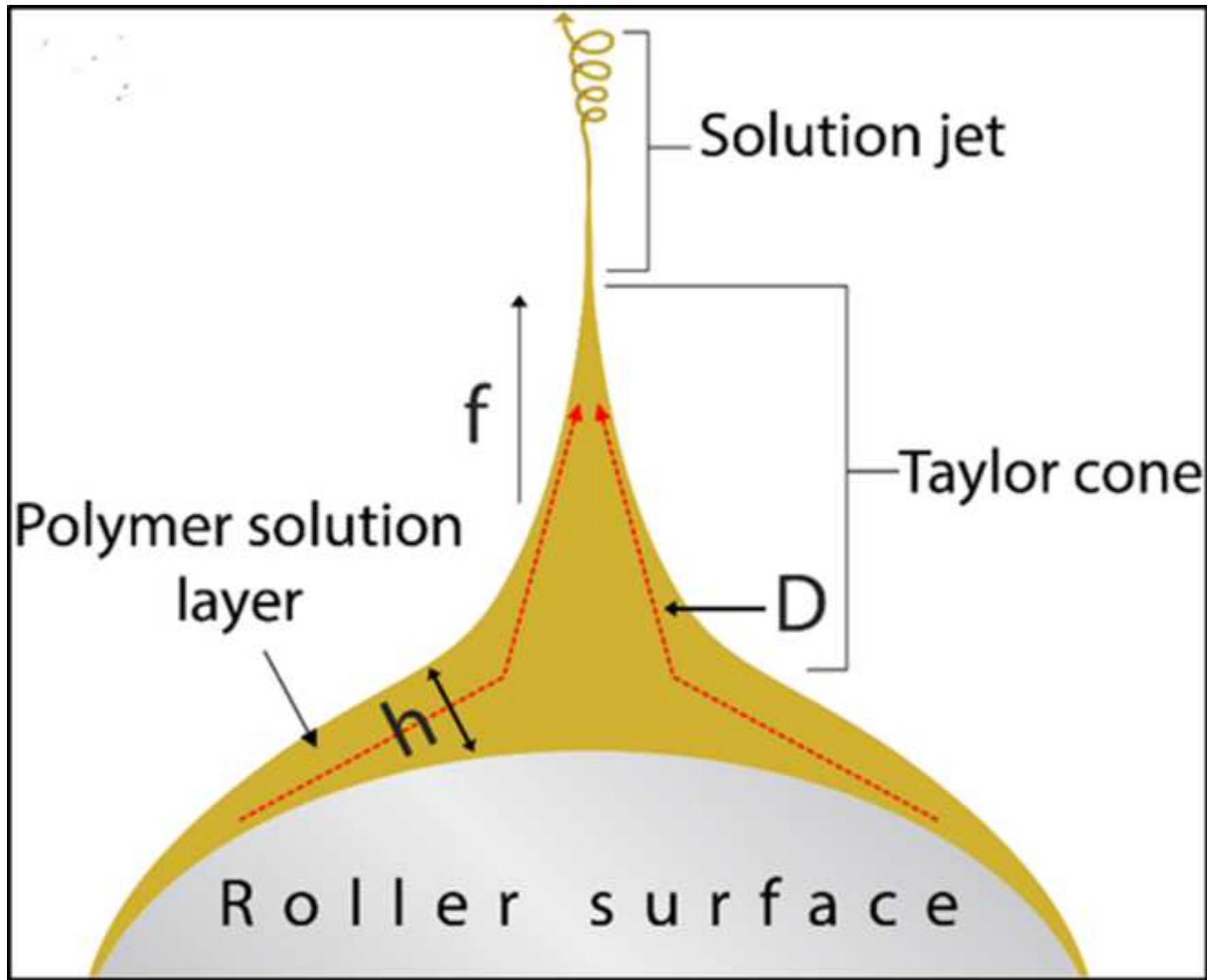


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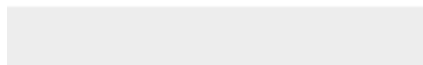


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