Chapter 1

Mechanical Force for Fabricating Nanofiber

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Additional information is available at the end of the chapter

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Abstract

Nanofiber has attracted increasing attention owing to its wide applications such as filtration, drug delivery, wound dressing, separator, etc. A lot of fabrication methods are developed in the last few decades, electrospinning method is the most frequently utilized method for producing nanofiber. However, electrospinning features a use of electrical field to produce nanofiber, which have obviously high production cost and a big burden on the environment. And several limitations are observed such as orientation of fibers and limited options of polymer and solvents, so many researchers try to develop more facile and more effective method for making nanofiber. In this chapter, recent developed fabrication methods, handspinning, direct writing, touch and brush spinning, are discussed and the advantages of each methods are described, respectively. They utilize a simple mechanical force instead of electrical force, which delivers great benefits to producing nanofiber such as orientation of fibers along with the force direction, reduction of every cost, availability of various options for selecting polymer and solvents, and a facility to design a pattern with high precision. Those innovative and novel methods will enable us to make functional nanofibers more effective than traditional methods; consequently, they will broaden the application of nanofibers.

Keywords: electrospinning, handspinning, touch and brush, direct writing, nanofibers

1. Introduction

Over the last few decades, nanotechnology has been attracted a lot of interest due to a potential for developing new materials and devices with a wide range of applications such as medicine, electronics, biomaterials and energy production [1–3]. Especially, nanofibers have been paid much attentions in various fields due to its unique characteristics e.g. high surface-to-mass ratio, flexibility, high porosity, ability to incorporate other materials, and other various

advantages, which allow opening up promising applications such as in filtration, scaffolds, wound healing, drug delivery, protective clothing, catalyst, sensors, energy harvest and storage, composite reinforcement, and many others [3–7].

Various techniques for fabricating polymeric fibers with diameters ranging from micron to nanometer scales have been developed and explored such as melt blowing [8], dry spinning [9], and wet spinning [10]; electrospinning is the most popular method for fabricating nanofiber among them [11]. The first introduction of the electrospinning was presented by Anton in 1934 [12], and it has attracted a lot of interests up to now because it has been regarded as the most effective way to produce continuous nanofibers on a large scale and adjust the fiber diameter from nanometers to micrometers. Electrospinning technique uses interactions between fluid dynamics, electrically charged surfaces and electrically charged liquids for fabricating nanofiber [13]. Typically, electrospinning apparatus comprises a high voltage power supply, a syringe needle connected to power supply, and a counter-electrode collector as shown in **Figure 1**. In electrospinning process, a strong electrical field is used to draw a polymer solution into fine filaments. When a sufficiently high electric voltage is applied to the polymer solution, the droplets that are ejected from the tip have an electrostatic repulsion force that counteracts the effect of surface tension, allowing the droplets to be stretched out to form nanofibers. The erupted and stretched filaments are travels through the air, the solvent evaporates leaving behind a polymer fibers to be collected on an electrically grounded collector.

Although electrospinning is an attractive method for fabricating nanofiber, it has been limited for fabricating nanofibers using polymer that have poor solubility in solvents and low electrical conductivity such as polyolefins (e.g., polyethylene and polypropylene) [13]. In addition, the use of electrical stretching force makes high electrical voltage necessary, indicating that it can produce high cost and excessive use of energy in production. Moreover, applying nanofiber to electrical devices requires reproducibly locating them in specific

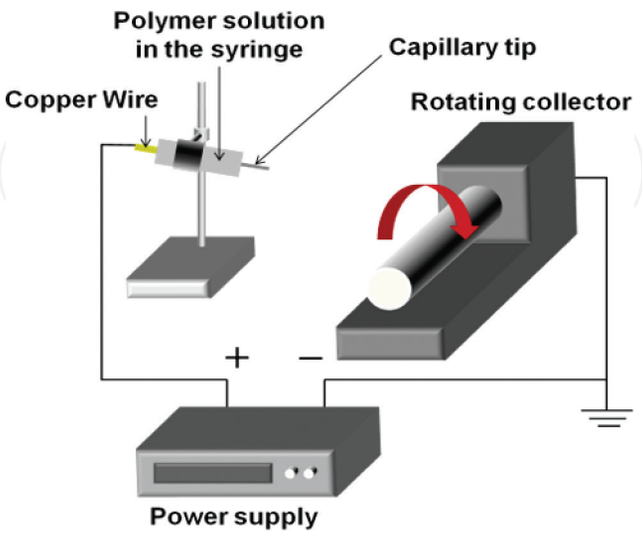

Figure 1. Schematic illustration of electrospinning apparatus.

position and orientations. However, electrospun nanofibers are difficult to apply to electrical device directly because electrospinning process typically produces fibers with random orientations without specific fabricating set-up. Thus, much effort has been devoted to developing and modifying the electrospinning method. Deitzel et al. presented a strategy that utilized electrostatic fields to control the deposition of electrospun nanofiber locating multiple field generator between tip and collector [14]. Tanase et al. reported orienting and assembling nanofibers suspended in a fluid solution using magnetic fields [15]. Zussman et al. used a disc collector instead of cylindrical collector in order to create a stronger converging electrostatic field and collect highly aligned nanofiber [16].

Apart from the electrospinning techniques, other approaches such as melt blowing, wet spinning, and dry spinning are also utilized for the fabrication of nanofibers. Melt blowing is a straightforward one step process which also one of the commonly used method for nonwovens production [17]. This method is performed by extruding a molten polymer and elongating the polymer stream coming out of the orifice by air-drag. The extrude fibers are solidified during the drawing process, and then collected on the surface of a collector. The advantages of melt blowing are high throughput rate, ease of preparing polymeric blends, suitability to the polymers having no appropriate solvent at room temperature, and unnecessary to removing the toxic solvent [18]. Even though the above advantages, melt blowing has some challenges such as the requirement of a high temperature which leads high energy cost and has possibility of polymer degradation, rapid solidification of the polymer in the orifice, and the difficulty in obtaining submicron fibers. The average diameter of melt blown nanofiber mainly depends on the throughput rate, solution viscosity, air temperature and air velocity, however, they are usually not smaller than micrometer without specially designed melt blowing setup such as using of special die with a small orifice or reducing the viscosity of the molten solution [17, 19]. On the other hands, dry spinning is used to form very thin fibers. In dry spinning process, the polymer solution dissolved in a volatile solvent is extracted through a spinneret with numerous holes (one to thousands) [20]. During the flight of the extracted nanofibers, heated air is used to evaporate the solvent so that the fibers solidify and are corrected. However, this method has been limited for selecting solvent due to safety and environmental concerns associated with solvent handling [21]. Wet spinning is the oldest method for fabricating fibers, which spinneret is submerged in a chemical bath to precipitate the fiber as it emerges [22]. A major different point of wet spinning with other spinning methods is this one which is spinning into a fluid with a much higher viscosity. The advantage of this method is that it does not require a purification process. However, wet spinning set-up is quite complex and expensive to install. In addition, this method can be applied to polymer which do not melt and dissolve only in non-volatile or thermal unstable solvents.

Herein, we introduce the recent novel developments of fabricating nanofiber apparatus; *Handspinning*, *Touch and Brush*, and *Direct Writing*. Those methods provide a solution that allowed us to overcome the limitations and issues in electrospinning and other spinning methods, and very simple and straightforward and versatile method that is universally applicable to any kind of polymer and solvents, it enables us to create a new type of polymeric nanofibers with exceptional properties.

2. Novel technologies for fabricating nanofibers

2.1. Handspinning

Recently, Lee et al. reported a simple and innovative method for fabricating nanofibers, called as Handspinning [23]. Handspinning was invented by mimicking commonly observed method in our daily lives such as the process of making cheese or noodles by hand-pulling, or making long and thin fiber-like structure from highly viscous liquid glue using two fingers, grabbing and subsequently pulling out the viscous material with thumb and index finger. Handspinning method relies on simple mechanical stretching force to fabricating nanofiber instead of an electrical force in electrospinning, which is a completely different mechanism for fabricating nanofiber. **Figure 2a–c** shows a schematic illustration and corresponding photographs of the nanofiber fabrication process via handspinning, and representative SEM image of a handspun nanofiber was presented in **Figure 2d**. **Figure 2e** shows that the simplest system of handspinning using only two fingers to make nanofibers.

The handspinning apparatus was designed to control processing parameters, i.e., pulling away speed (PAS, cm/s), pulling away distance (PAD, cm), and plate area (PA, cm^2), instead of voltage, tip to collector distance, feed rate which are processing parameters of electrospinning. Handspinning provides a number of options for polymers and solvents because their electrical properties are not relevant at all. Watanabe et al. reported that the diameter and surface morphologies of handspun fiber depend on solvent systems and processing conditions to control simple mechanical force [24]. They exploit a typical polyolefins, polypropylene, to investigate the utilization of handspinning. It is noticeable that polypropylene successfully fabricated in single solvent system (cyclohexane) via handspinning (**Figure 3a**), while it was not obtained

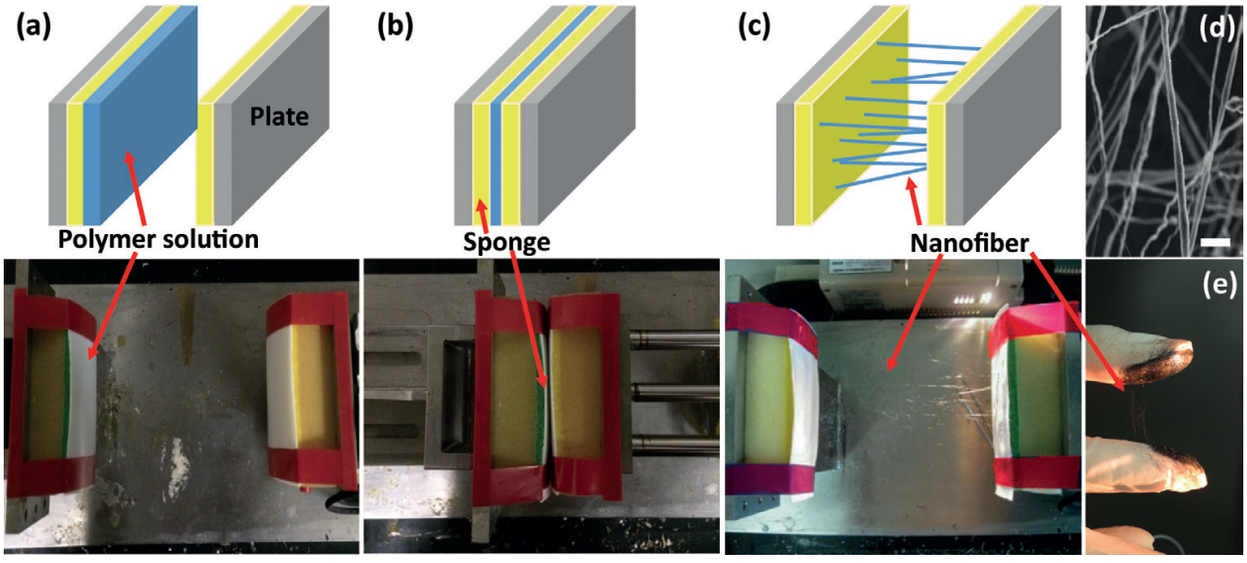

Figure 2. (a–c) Schematic illustrations and corresponding photographs of the nanofiber fabrication process via handspinning; (d) representative SEM image of a handspun nanofiber (scale bar = 10 μm); (e) photograph showing handmade nanofibers using two fingers (Reproduced with permission from Ref. [17]. Copyright 2016, Nature Publishing Group).

by electrospinning system. In addition, the morphologies of handspun and electrospun nanofibers were significantly different in same solvent system. The handspun polypropylene from the mixed solvent system shows smooth surface (**Figure 3b**), whereas the electrospun polypropylene exhibited rough surfaces with the collapsed morphology (**Figure 3c**).

Also, a significant difference in polymer chain conformation between the handspun and electrospun nanofiber was observed, and it was attributed to mechanical stretching force. The conformation of polypropylene was confirmed by FT-IR spectroscopy (**Figure 4**), which has been well-known to be a useful method to determine molecular and chain conformation. In FT-IR spectrum, it is clearly observed that the helical conformations were produced mainly when nanofiber electrospun, while hansdpun nanofiber appeared the long stands in the trans-planar conformation [24]. These results strongly suggest that the handspinning process produces more stretched fiber than the electrospun fiber, resulting in stiffer and stronger nanofiber [24].

Another advantage of handspinning is that it enables to concentrating nanofiller such as carbon nanotube (CNT), which can improve thermal and mechanical properties of nanofiber. Incorporation of a high concentration of CNTs in a polymer matrix without aggregation and localization of the CNTs is difficult because they tend to make a bundle, resulting in their being poor dispersed in the polymer matrix and the deterioration of the properties of the material [25, 26]. In addition, increasing the concentration of filler in nanofiber is limited [27]. In handspinning, the process relies only on a simple, mechanical pulling motion, hence the effect of the concentration of CNTs on the process likely is negligible. In addition, the simple mechanical stretching force in handspinning is more effective to align the CNTs in the nanofiber than the force induced by the electric field in electrospinning. **Figure 5** shows typical SEM and TEM images of electrospun and handspun PVAc/CNT nanofibers with various concentration of CNTs. It is worth to note that handspun nanofibers are aligned quite well compared to electrospun nanofibers, which typically are distributed randomly. Since the force is applied uniaxially to the polymer solution by a pull-out motion, nanofibers are fabricated along the axis in the direction of the operation, leading to well-aligned nanofibers. In addition, in TEM image, it clearly indicates that the orientation of the CNTs in the PVAc matrix was dependent on the fabrication method due to the different applied force. The pulling out from mechanical force in handspinning process affects the distribution of the filling materials in nanofiber. On

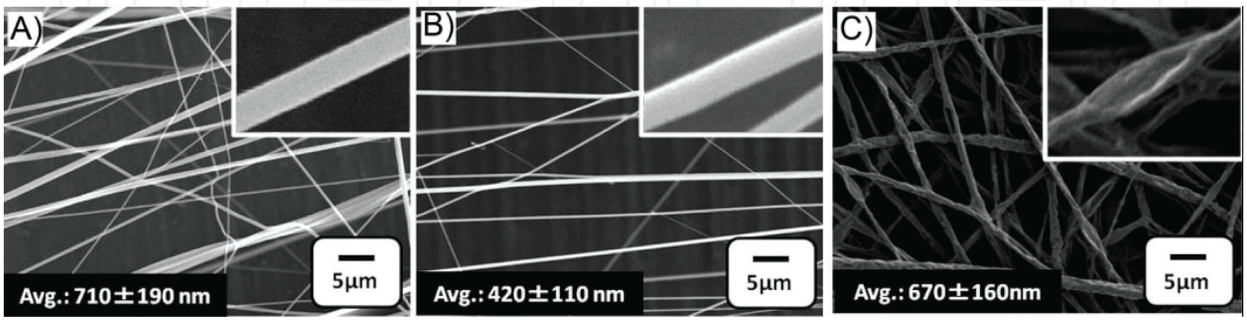

Figure 3. SEM images of handspun PP nanofibers obtained from the single solvent system (a: cyclohexane), mixed solvent system (b: cyclohexane/acetone/DMF = 80/10/10 wt%), and (c) electrospun PP nanofibers. PAD = 10 cm, TCD = 15 cm. The insets show the magnified SEM images (Reproduced with permission from Ref. [18]. Copyright 2011, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim).

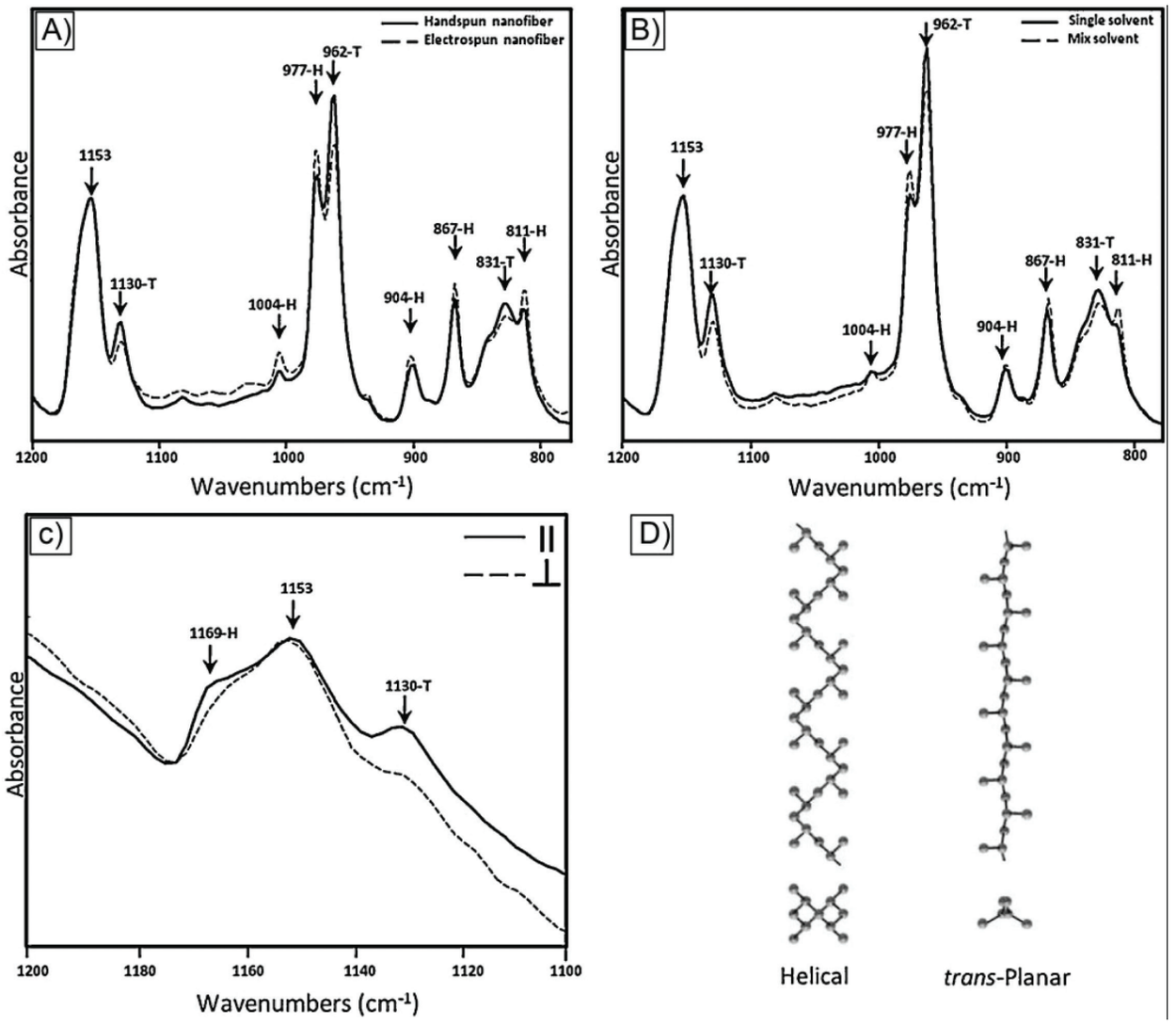

Figure 4. (a) FT-IR attenuation total reflectance (ATR) spectra of handspun and electrospun PP nanofibers. (b) FT-IR ATR spectra of handspun PP nanofibers obtained from single-solvent (cyclohexane) and mixed-solvent system (cyclohexane/acetone/DMF = 80/10/10 wt%). T: transplanar, H: helical. (c) Polarized FT-IR spectra of handspun PP nanofibers (parallel and perpendicular to the fiber axes in the macroscopically aligned fibers). T: trans-planar, H: helical. (d) Schematic representation of helical and trans-planar conformations of PP polymer chain (Reproduced with permission from Ref. [18]. Copyright 2011, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim).

the other hands, in electrospinning process, the CNTs are not aligned compared to handspun nanofiber relatively, because the electrical treatment did not be translated to mechanical force to stretch the CNTs. Thus, this novel fabrication method, handspinning, leads to well-defined nanofibers with a parallel orientation and uniaxial alignment of the CNTs to the fibers, all of which are induced by simple mechanical force.

The handspun nanofibers exhibit the enhanced physical properties such as mechanical and thermal properties. Handspinning process produces more stretched fiber than the electrospinning process, indicating that the pulling mechanical force in the handspinning induced the alignment of the polymer chains compared with electrospun nanofiber as above mention in **Figure 4** [23]. Thus, the handspinning is beneficial in that it enhances the tensile strength of the fiber by inducing

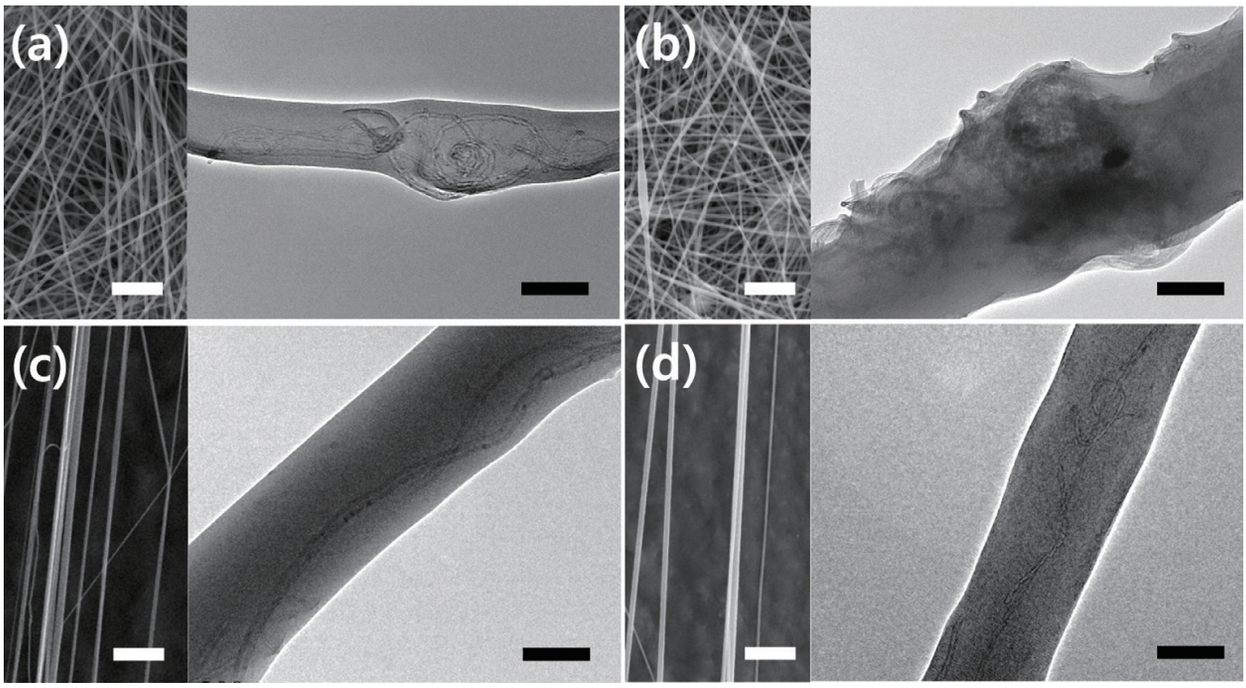

Figure 5. SEM (left) and TEM (right) images of electrospun nanofibers: (a) 0.5 wt%, (b) 1 wt% of CNTs; handspun nanofibers: (c) 0.5 wt%, (d) 1 wt% of CNTs (SEM scale bar = 5 μm, TEM scale bar = 100 nm) (Reproduced with permission from Ref. [17]. Copyright 2016, Nature Publishing Group).

polymer chain alignment. The CNTs distribution also highly affects to mechanical property of nanofiber. The tensile force was not distributed evenly along the fiber in the aggregated state; it was focused on local points where the CNT aggregates were located in the nanofiber, leading to lower tensile strength. The handspun nanofiber can achieve the evenly distributed CNTs along the fiber as observed in TEM (**Figure 5c**, **d**), thus, the handspinning method enhanced the mechanical properties of the nanofibers by a simple change in the fabrication method. Moreover, the handspun nanofibers are able to retain larger amount of CNTs. Increasing the amount of CNTs in nanofiber dramatically increased Young's modulus and tensile strength as presented in **Figure 6**. The handspinning method, in which the concentration of CNT could be increased, achieved a Young's modulus that was 1.8 times was greater than that of the electrospinning method. At the same CNT concentration for both methods, the tensile strength 2.4 times greater for the handspinning method, making it a powerful tool to attain strong nanofibers when the orientation of the CNTs is important. All related observations indicated that handspinning provides a versatile and straightforward route to obtain well-defined nanofibers. It provides a solution that allowed us to overcome the limitations in electrospinning, such as the low mechanical properties due to the limited amount of nanofillers in the polymer matrix. In addition, handspinning is universally applicable to any kinds of polymers and solvents, it enables us to create a new type of reinforced polymeric composite nanofibers with exceptional properties.

The current handspinning system also has several drawbacks. The low throughput of handspinning could be one of the drawbacks. In addition, the uniformity of nanofiber diameter relatively lows compared to conventional spinning method. Current system is presented as the proof of concept to fabricate nanofiber via simple mechanical force, it should be improved

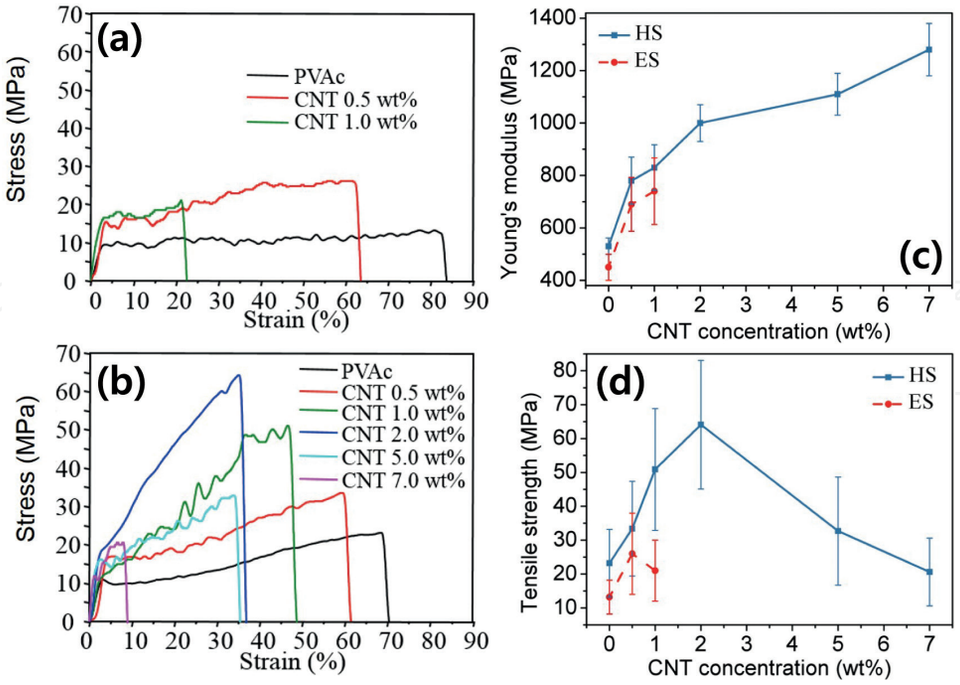

Figure 6. Stress-strain curves measured with the various CNT concentrations (a) single electrospun nanofibers; (b) single handspun nanofibers; (c and d) tensile strength and Young's modulus of single electrospun and handspun nanofibers extracted from the stress-strain curves (Reproduced with permission from Ref. [17]. Copyright 2016, Nature Publishing Group).

the instrumental set-up simultaneously achieving high efficiency as well as high quality of nanofibers. The improvement of handspinning equipment has a potential for leading to higher throughput, possibly applicable to actual application. For example: (i) In the presented set-up, pulling away speed is 40 cm/s. This indicates the length of a single fiber is 40 cm. If 100 nanofibers are produced, total length of fibers per a single operation is 40 m, indicating its potential towards comparable throughput to conventional spinning method. (ii) By making the size of plates where polymer solution is dispensed large, much larger amount of fibers can be produced. (iii) If solution dispensing is automated through the plates, time can be significantly saved. Moreover, the effect of each parameters of handspinning should be investigated, which is still not uncovered. Therefore, development of handspinning instrument is required, and the investigation of handspinning should be conducted more deeply.

2.2. Direct writing

Flexibility of electronic devices is an essential character for future smart electronic devices i.e. flexible solar cells [28], flexible displays [29], and sensor tapes [30]. Nanofibers with high conductivity as well as mechanical flexibility play a key role for constructing flexible electronic device. Especially, fabricating the ultra-long length fiber is significant in the fabrication of large-sized flexible electronics, and it also affects in manufacturing efficiency. There have been many efforts to develop the flexible device, however, precise position control and the convenient assembly process are yet to be realized in scalable production of flexible electronics.

The simplest way to fabrication of nanofiber is direct drawing from a polymer solution using a glass micropipette or an ordinary pen tip [31]. This directing writing method has been

proposed by lots of literature, and they successfully constructed complex structures, patterns, and grids [32–34]. However, the drawing speed and fiber's length are too low and short to utilize in practical applications, and it fabricates the large-size macro-fiber rather than submicron or nanofiber, because drawn fibers from liquid phase are hard to bear the tensile stress. It is known that thin fibers are usually fragile and can be easily broken by large tensile stress at high drawing speed. Ondarcuhu et al. fabricated a sing fiber using a micropipette as a drawing tool [31]. In drawing method, the fiber is grown along the nucleation and precipitation of solute material in the liquid meniscus. It was an innovative and facile method to make single nanofiber, however, it was limited in draw rate less than 100 μm/s and the maximum length only reached 1 mm. Suryavanshi et al. controlled the meniscus to improve drawing speed and manage to place the fibers in well-aligned pattern [32]. However, the drawing speed was lower than 1 mm/s, which was still too low to satisfy the need for scalable mass production. Recently, Huang et al. demonstrated a simple hand-writing process to fabricate the ultralong fibers with high drawing speed as building blocks for flexible electronic devices [35]. They draw fiber from a typical pen tip by using a high molecular weight of PEO solution with sodium dodecyl sulfonate as surfactants, and added CNTs for giving a conductivity to fiber. The surfactants used for reducing the surface tension of solution, resulting that the diameter of fiber decrease down to nanosize. The simple touch and drawing process can fabricate the single nanofiber (**Figure 7a–c**). During the drawing process, the fibers diameter shrink drastically up to 60 nm due to rapid solvent evaporation. A use of typical pen instead of micropipette prevents the deformation of fiber which happens when the fiber were still in liquid phase. **Figure 7e** shows a uniform single fiber collected on glass slides, crossing 20 cm distance, and corresponding SEM image was also presented in **Figure 7f**.

This direct writing method has several benefits compared with previous reported drawing methods. The drawing speed can achieve 10 cm/s, which is 100 times much faster, and the total time needed to produce one fiber is primarily the time of suspension. It allows us to obtain the nanofiber efficiently. Moreover, the CNTs can be aligned efficiently which was observed in high resolution SEM images (**Figure 8**). As a result, thinner fibers represent higher conductivity than thicker ones and show significantly enhanced conductivity compared with isotropic CNT thin film samples. In addition, the direct written CNT/PEO fibers exhibit excellent flexibility, which is essential for flexible electronic applications.

Accurately placing a single nanofiber on desired plate is also a significant advantage of direct writing method. This method can demonstrate convenient and efficient assembly of fiber arrays, and can make flexible and conducting circuits across more than 10 cm area. They draw conducting fiber lines on the slide glass with designed pattering. Two drawn nanofibers are precisely located with desired angles of 0°, 30°, 45°, 60° and 90° (**Figure 9a**). In addition, three or four drawn fibers are perfectly cross at one points, equally dividing 360° into six and eight parts with no significant deviation (**Figure 9b-d**). It is worth noting that if two fibers are prepared in rapid sequence to create merged joints when they are not fully dried, the cross-point would be more reliable electrical connection than simple surface contact. By using multiple tips for drawing, it also achieves both fast assembly and precise control of fibers. Therefore, accurate positioning control and fast assembly have been demonstrated conveniently through simple writing method, which could be applied to flexible electronic device application with mechanical flexibility.

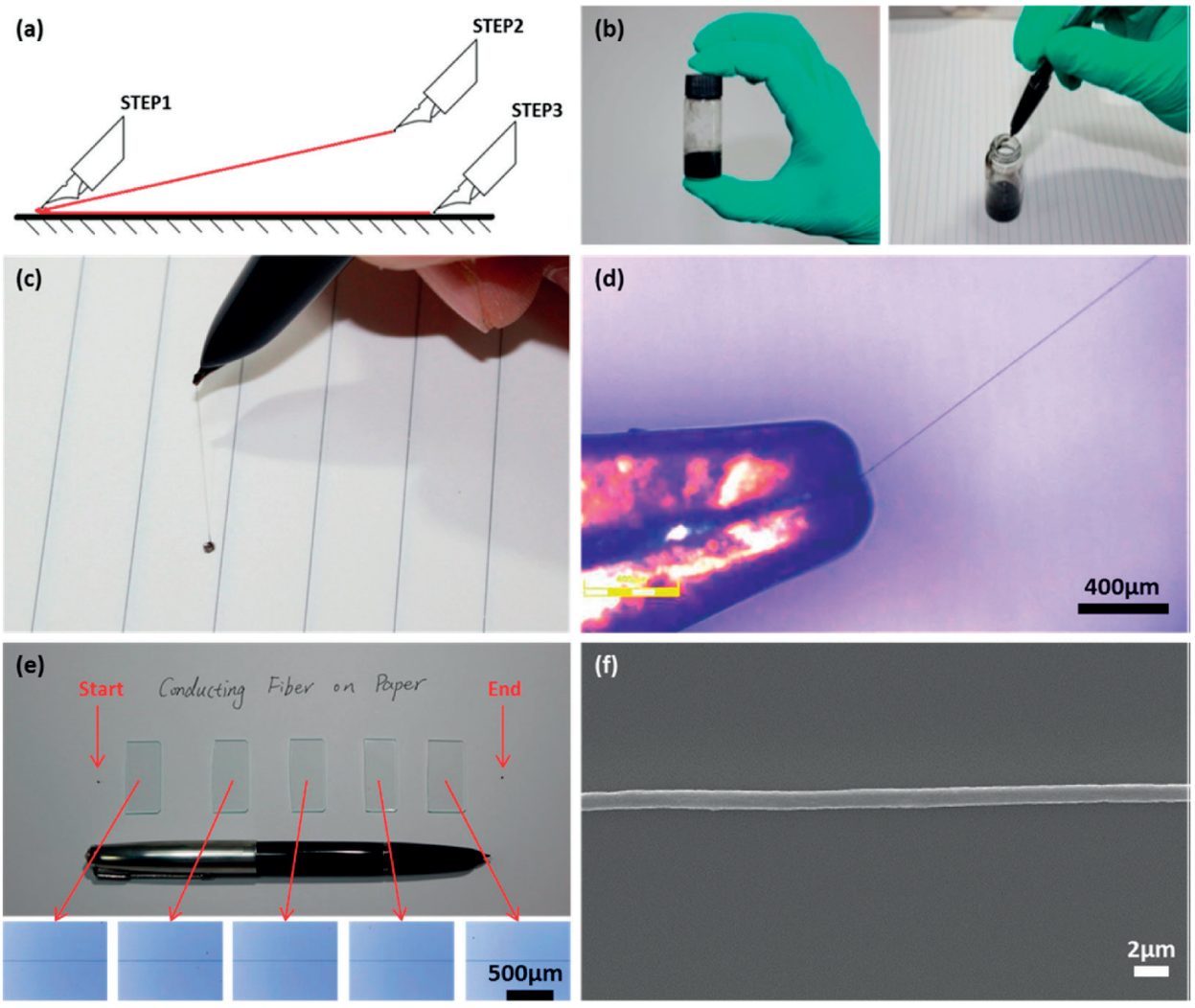

Figure 7. (a–c) A schematic and photographs of the manufacturing procedure, (d) optical microscopy of an ultralong fiber being drawn by the pen tip, (e) an ultralong and homogeneous fiber and its optical microscope images of each segment, (f) SEM image of the fiber (Adapted with permission from Ref. [29]. Copyright 2015, American Chemical Society).

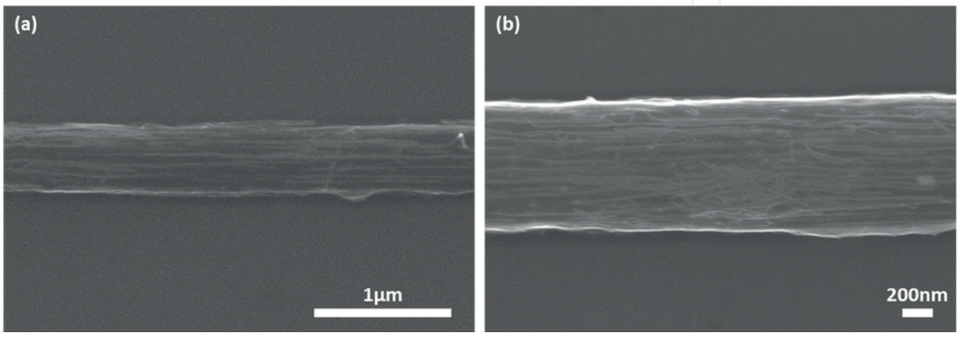

Figure 8. Confirmation of CNTs configuration in a (a) 300 nm and (b) 1 μm fiber via SEM observation (Reproduced with permission from Ref. [29]. Copyright 2015, American Chemical Society).

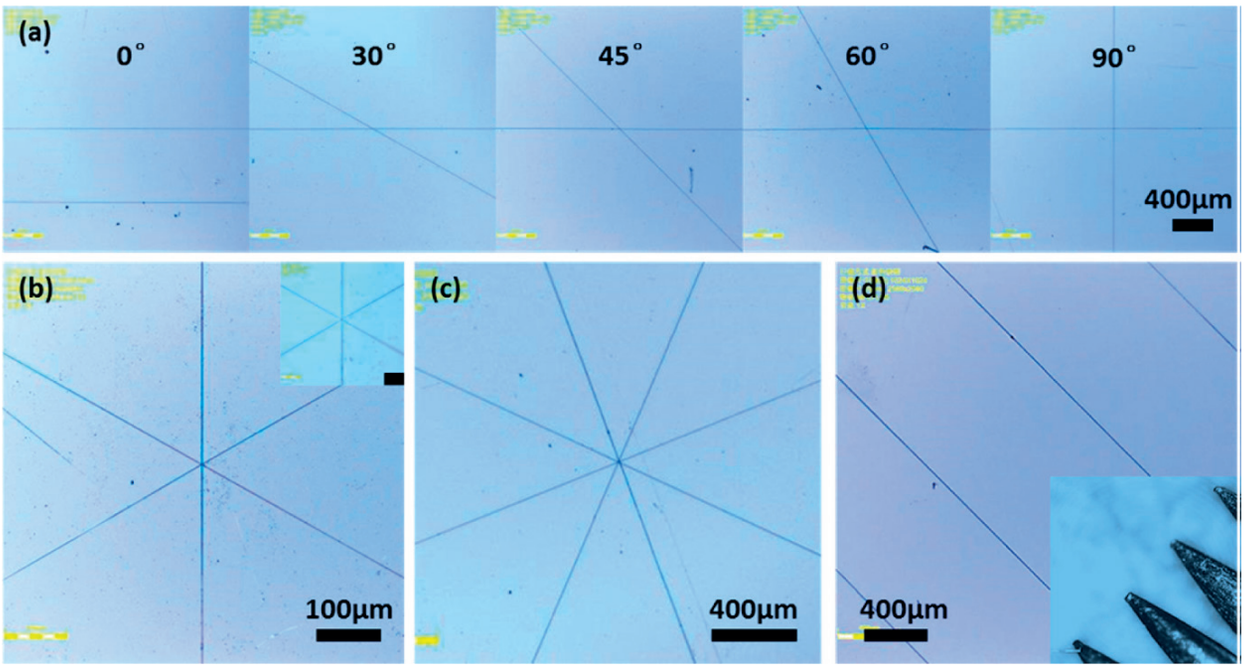

Figure 9. Demonstration of how precisely the fibers are manipulated (a) Two fibers located to form angles of 0°, 30°, 45°, 60°, and 90°; (b) three fibers that cross at one point, also observed to cross well under higher magnification (smaller figure on the top right corner, scale bar 20 μm); (c) four fibers that cross approximately at one point; (d) four parallel fibers written at one time by four aligned needle tips. (Adapted with permission from Ref. [29]. Copyright 2015, American Chemical Society).

2.3. Touch and brush spinning

The direct drawing method might be the simplest method for fabricating nanofiber. However, the drawing method has been limited in scale up and mass production, resulting that it cannot find practical applications. Recently, Tokarev et al. developed a facile and straightforward apparatus for extracting nanofibers from polymer solutions using a rotating rod or a round brush, called Touch and Brush method, which is a scalable method of nanofiber and easily fabricable 3D-scaffolds structure [36]. This method consisted with a glass rod on rotating stage (whose diameter can be chosen over a wide range of a few centimeters to more than 1 m) and a polymer solution is supplied from a needle of a syringe pump which faces the glass rod. This simple setup can be built by gluing a rod to a rotating stage from which fiber can be spun from a free-liquid surface. Simple schematic illustration was depicted in **Figure 10**. The distance between the droplet and tip of the glass rod is modulated so that the glass rod contacts the polymer droplet as it rotates. A thin filament forms after the initial touch process, and as the stage rotates, the filament stretched and fiber length increases with the diameter decreasing. The diameter of touch-spun nanofiber is modulated precisely in the range 40 nm to 5 μm by adjusting the rotational speed and polymer concentration. The fiber diameter decreases with increasing rotational speed and decreasing polymer concentration. The significant difference of the touch-spinning from other commonly used fabrication method is that it uses a simple mechanical force to manipulation of nanofiber, which is similar with handspinning method above mentioned. This simple and novel method was simply prepared with inexpensive setup that does not require special training, skills, or specialized equipment. Owing to the simplicity and ability of touch-spinning, the 3D customized scaffolds of different dimensions, shapes, mesh sizes, and fiber alignments can be easily fabricated in minutes.

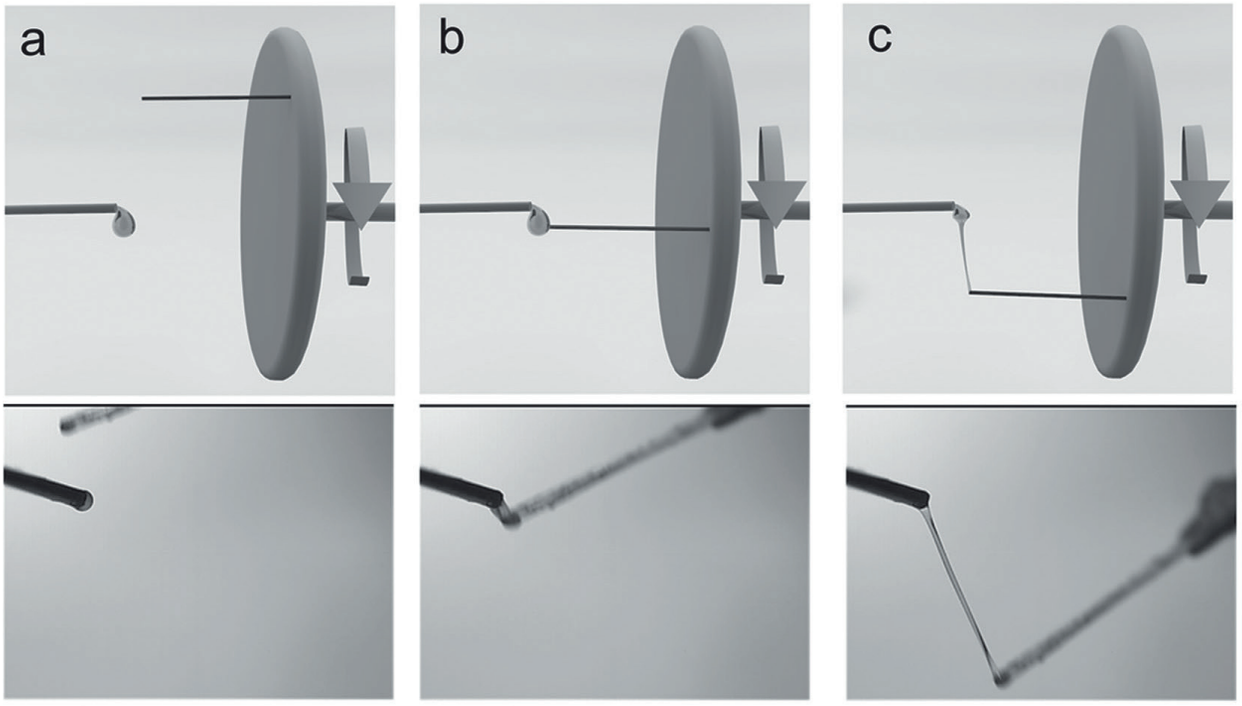

Figure 10. Schematic illustration of simple touch-spinning process a) a rotating rod on the stage and a polymer droplet, b) the rotating rod touches the droplet of the polymer solution, c) a liquid filament is formed between the rod and the tip while the rod continues rotation. (Reproduced with permission from Ref. [30]. Copyright 2015, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim).

They also realized the scalability and simplicity of touch-spinning method by using a round hairbrush composed of the order of 600 filaments instead of single rod (**Figure 11**). The brush connected and rotated to an electrical motor via brush grip, and polymer solutions supplied onto a Teflon film placed underneath the round brush. The filaments on the brush touch the polymer solution during the rotating, lots of nanofibers are spun from the free-liquid surface. From this novel method, the total length of the fibers produced by the 600-filament brush with 60 mm diameter at 3000 rpm in 5 min is 1700 km [36]. It is enough to utilize for an industrial manufacturing or typical tissue-engineering.

Moreover, this new method is a facile to wind a single filament into unidirectional, orthogonal, or randomly oriented 2D and 3D meshes with controlled density, thickness, and combinations

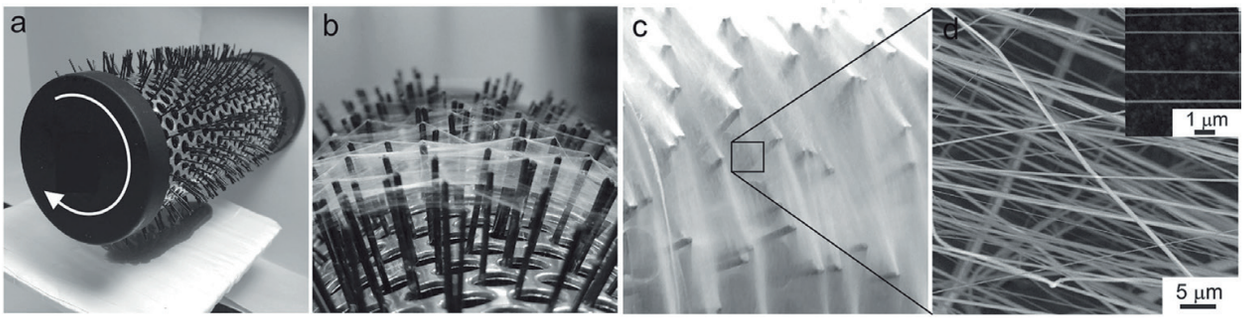

Figure 11. (a) Photographs of nanofiber fabrication process via brush-spinning method. (b) Nanofibers collected on the hairbrush rotated at 3000 rpm for 1 min and (c) for 5 min of spinning. (d) SEM image of brush-spun nanofibers (Adapted with permission from Ref. [30]. Copyright 2015, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim).

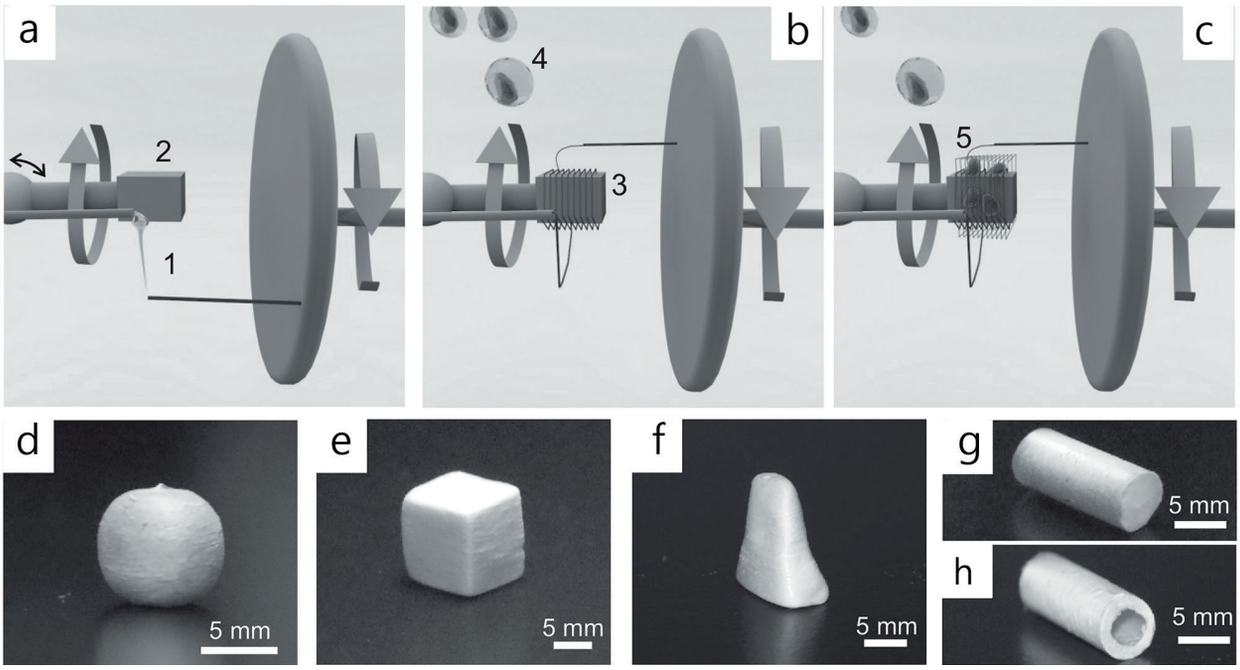

Figure 12. (a–c) Schematic illustration of the preparation of 3D scaffolds, and (d–h) different shapes and sizes of 3D scaffolds obtained by winding nanofibers (Reproduced with permission from Ref. [30]. Copyright 2015, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim).

of different fibers and materials in the scaffolds. When it considered applications of nanofiber for tissue engineering scaffolds, it could provide a very fast and practical way to produce scaffolds with controlled mesh size. Manufacturing process for 3D scaffolds was depicted in **Figure 12a–c**. After initial touch, the fiber drawn by the rod is wound onto the desired frame. The frame having complicated geometries can be easily wound because the frame can be tilted at any angle. The density of fiber on the frame can be regulated by the motion of the matrix that shuttles back and forward. From this method, different shapes and sizes of 3D scaffolds can be easily obtained by winding nanofibers onto supporting frames. Several examples of resulting matrix are presented in **Figure 12d–h**. The examples prove the capability of the touch-spinning method for fabrication of biomimetic scaffolds on different scales from macroscopic shape and dimensions to microscopic fiber dimensions and alignment into various meshes that are relevant to mesh-like structures in human tissues. It strongly implies that it could be utilized in the other various application such as filtration [37] or superhydrophobic coatings [38]. Therefore, this facile and straightforward method allows us to fabricate a productive amount of nanofiber and manufacture the 3D scaffold structure in few minute, providing an effective pathway to utilize the nanofibers.

3. Summary

Recently, there has been a lot of efforts to develop the nanofiber fabrication methods to overcome the limitations of conventional spinning method. The most widely utilized method, electrospinning, features a utilization of electrical force to fabricating nanofiber. Although

Handspinning	Direct writing	Touch and brush spinning
Facile: easy	Facile: easy	Facile: middle
Productivity: low	Productivity: low	Productivity: high
Alignment: high	Alignment: high	Alignment: low
Fiber control: unable	Fiber control: able	Fiber control: unable
Fiber uniformity: low	Fiber uniformity: middle	Fiber uniformity: low
Energy cost: low	Energy cost: low	Energy cost: low

Table 1. Comparison of handspinning, direct writing, touch and brush spinning.

electrospinning brings a highly development in the use of nanofiber, it has remained several challenges originated in the using of electrical force. The raising issues in nanofiber fabrication are the improving productivity, the fiber alignment, the enhancing the properties, and the simplicity of realization. In this chapter, we summarized the recent development of fabrication methods, handspinning, direct writing spinning, and touch/brush spinning, they provide an effective pathway to create new-types of nanofiber with outstanding properties (**Table 1**). All suggested methods use a simple mechanical stretching force, as it does not require an electrical force, which results in well-oriented polymer fibers along with the force direction, and avoids high cost and excessive use of energy in production, and offers a number of options for polymers and solvents because electrical properties are not relevant at all. Also, the spun nanofibers are expected to have enhanced mechanical properties due to change of chain conformation. Those method enable to design a desired pattern with high precision due to its easy construction, providing a potential for convenient and scalable fabrication of flexible electronic devices. Therefore, we certain that the development of fabricating methods will accelerate new applications, such as 3D scaffold, filtration, electrical devices, and those straightforward techniques open commercial opportunities for hundreds of ideas developed in the academic fields.

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References

[1] Lee H, Ryu J, Kim M, Im SS, Kim IS, Sohn D. Trace the polymerization induced by gamma-ray irradiated silica particles. Radiation Physics and Chemistry. 2016;**125**:160-164

[2] Lee H, Jeon Y, Lee Y, Lee SU, Takahara A, Sohn D. Thermodynamic control of diameter-modulated aluminosilicate nanotubes. Journal of Physical Chemistry C. 2014;**118**(15):8148-8152

[3] Lee H, Xu G, Kharaghani D, Nishino M, Song KH, Lee JS, Kim IS. Electrospun tri-layered zein/PVP-GO/zein nanofiber mats for providing biphasic drug release profiles. International Journal of Pharmaceutics. 2017;**531**(1):101-107

[4] Lee H, Kim M, Sohn D, Kim SH, Oh S-G, Im SS, Kim IS. Electrospun tungsten trioxide nanofibers decorated with palladium oxide nanoparticles exhibiting enhanced photocatalytic activity. RSC Advances. 2017;**7**(10):6108-6113

[5] Lee H, Phan D-N, Kim M, Sohn D, Oh S-G, Kim S, Kim I. The chemical deposition method for the decoration of palladium particles on carbon nanofibers with rapid conductivity changes. Nanomaterials. 2016;**6**(12):226

[6] Lee H, Nagaishi T, Phan D-N, Kim M, Zhang K-Q, Wei K, Kim IS. Effect of graphene incorporation in carbon nanofiber decorated with TiO_2 for photoanode applications. RSC Advances. 2017;**7**(11):6574-6582

[7] Lee H, Hun Song K, Soon Im S, Jung J-S, Jatoi AW, Kim IS. Fabrication of poly(vinyl alcohol)/cellulose nanofiber derivative from Kenaf bast fiber via electrospinning. Nanoscience and Nanotechnology Letters. 2016;**8**(2):168-172

[8] Fambri L, Pegoretti A, Fenner R, Incardona SD, Migliaresi C. Biodegradable fibres of poly(l-lactic acid) produced by melt spinning. Polymer. 1997;**38**(1):79-85

[9] Zhang M, Ogale AA. Carbon fibers from dry-spinning of acetylated softwood kraft lignin. Carbon. 2014;**69**:626-629

[10] Phillips DM, Drummy LF, Naik RR, Long HCD, Fox DM, Trulove PC, Mantz RA. Regenerated silk fiber wet spinning from an ionic liquid solution. Journal of Materials Chemistry. 2005;**15**(39):4206-4208

[11] Lee H, Koo JM, Sohn D, Kim I-S, Im SS. High thermal stability and high tensile strength terpolyester nanofibers containing biobased monomer: Fabrication and characterization. RSC Advances. 2016;**6**(46):40383-40388

[12] Anton F. Process and apparatus for preparing artificial threads. United States Patent Application. Journal. 1934, 1975504

[13] Li D, Xia Y. Electrospinning of nanofibers: Reinventing the wheel?. Advanced Materials. 2004;**16**(14):1151-1170

[14] Deitzel JM, Kleinmeyer JD, Hirvonen JK, Beck Tan NC. Controlled deposition of electrospun poly(ethylene oxide) fibers. Polymer. 2001;**42**(19):8163-8170

[15] Tanase M, Bauer LA, Hultgren A, Silevitch DM, Sun L, Reich DH, Searson PC, Meyer GJ. Magnetic alignment of fluorescent nanowires. Nano Letters. 2001;**1**(3):155-158

[16] Theron A, Zussman E, Yarin AL. Electrostatic field-assisted alignment of electrospun nanofibres. Nanotechnology. 2001;**12**(3):384

[17] Ellison CJ, Phatak A, Giles DW, Macosko CW, Bates FS. Melt blown nanofibers: Fiber diameter distributions and onset of fiber breakup. Polymer. 2007;**48**(11):3306-3316

[18] Zhou H, Green TB, Joo YL. The thermal effects on electrospinning of polylactic acid melts. Polymer. 2006;**47**(21):7497-7505

[19] Podgórski A, Bałazy A, Gradoń L. Application of nanofibers to improve the filtration efficiency of the most penetrating aerosol particles in fibrous filters. Chemical Engineering Science. 2006;**61**(20):6804-6815

[20] Ohzawa Y, Nagano Y, Matsuo T. Studies on dry spinning. I. Fundamental equations. Journal of Applied Polymer Science. 1969;**13**(2):257-283

[21] Horáček I, Kalíšek V. Continuous dry spinning–hot drawing preparation of fibers. Journal of Applied Polymer Science. 1994;**54**(11):1751-1757

[22] Cong H-P, Ren X-C, Wang P, Yu S-H. Wet-spinning assembly of continuous, neat, and macroscopic graphene fibers. Scientific Reports. 2012;**2**:613

[23] Lee H, Watanabe K, Kim M, Gopiraman M, Song K-H, Lee JS, Kim IS. Handspinning enabled highly concentrated carbon nanotubes with controlled orientation in nanofibers. Scientific Reports. 2016;**6**:37590

[24] Watanabe K, Kim BS, Enomoto Y, Kim IS. Fabrication of uniaxially aligned poly (propylene) nanofibers via handspinning. Macromolecular Materials and Engineering. 2011;**296**(6):568-573

[25] Chen Q, Dai L, Gao M, Huang S, Mau A. Plasma activation of carbon nanotubes for chemical modification. The Journal of Physical Chemistry. B. 2001;**105**(3):618-622

[26] Spinks GM, Shin SR, Wallace GG, Whitten PG, Kim SI, Kim SJ. Mechanical properties of chitosan/CNT microfibers obtained with improved dispersion. Sensors and Actuators B: Chemical. 2006;**115**(2):678-684

[27] Han T, Yarin AL, Reneker DH. Viscoelastic electrospun jets: Initial stresses and elongational rheometry. Polymer. 2008;**49**(6):1651-1658

[28] Haining C, Liqun Z, Huicong L, Weiping L. Growth of ZnO nanowires on fibers for one-dimensional flexible quantum dot-sensitized solar cells. Nanotechnology. 2012;**23**(7):075402

[29] Lee J, Lee P, Lee H, Lee D, Lee SS, Ko SH. Very long Ag nanowire synthesis and its application in a highly transparent, conductive and flexible metal electrode touch panel. Nanoscale. 2012;**4**(20):6408-6414

[30] Wang X, Drew C, Lee S-H, Senecal KJ, Kumar J, Samuelson LA. Electrospun nanofibrous membranes for highly sensitive optical sensors. Nano Letters. 2002;**2**(11):1273-1275

[31] Ondarçuhu T, Joachim C. Drawing a single nanofibre over hundreds of microns. EPL (Europhysics Letters). 1998;**42**(2):215

[32] Suryavanshi AP, Hu J, Yu MF. Meniscus-controlled continuous fabrication of arrays and rolls of extremely long micro- and nano-fibers. Advanced Materials. 2008;**20**(4):793-796

[33] Hu J, Yu M-F. Meniscus-confined three-dimensional electrodeposition for direct writing of wire bonds. Science. 2010;**329**(5989):313-316

[34] Nain AS, Sitti M, Jacobson A, Kowalewski T, Amon C. Dry spinning based spinneret based tunable engineered parameters (STEP) technique for controlled and aligned deposition of polymeric nanofibers. Macromolecular Rapid Communications. 2009;**30**(16):1406-1412

[35] Huang S, Zhao C, Pan W, Cui Y, Wu H. Direct writing of half-meter long CNT based fiber for flexible electronics. Nano Letters. 2015;**15**(3):1609-1614

[36] Tokarev A, Asheghali D, Griffiths IM, Trotsenko O, Gruzd A, Lin X, Stone HA, Minko S. Touch- and brush-spinning of nanofibers. Advanced Materials. 2015;**27**(41):6526-6532

[37] Qin X-H, Wang S-Y. Filtration properties of electrospinning nanofibers. Journal of Applied Polymer Science. 2006;**102**(2):1285-1290

[38] Tuteja A, Choi W, Ma M, Mabry JM, Mazzella SA, Rutledge GC, McKinley GH, Cohen RE. Designing superoleophobic surfaces. Science. 2007;**318**(5856):1618-1622

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