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Artificial cilia fabricated with a roll-to-roll filament pullout process

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Artificial cilia fabricated with a roll-to-roll filament pullout process

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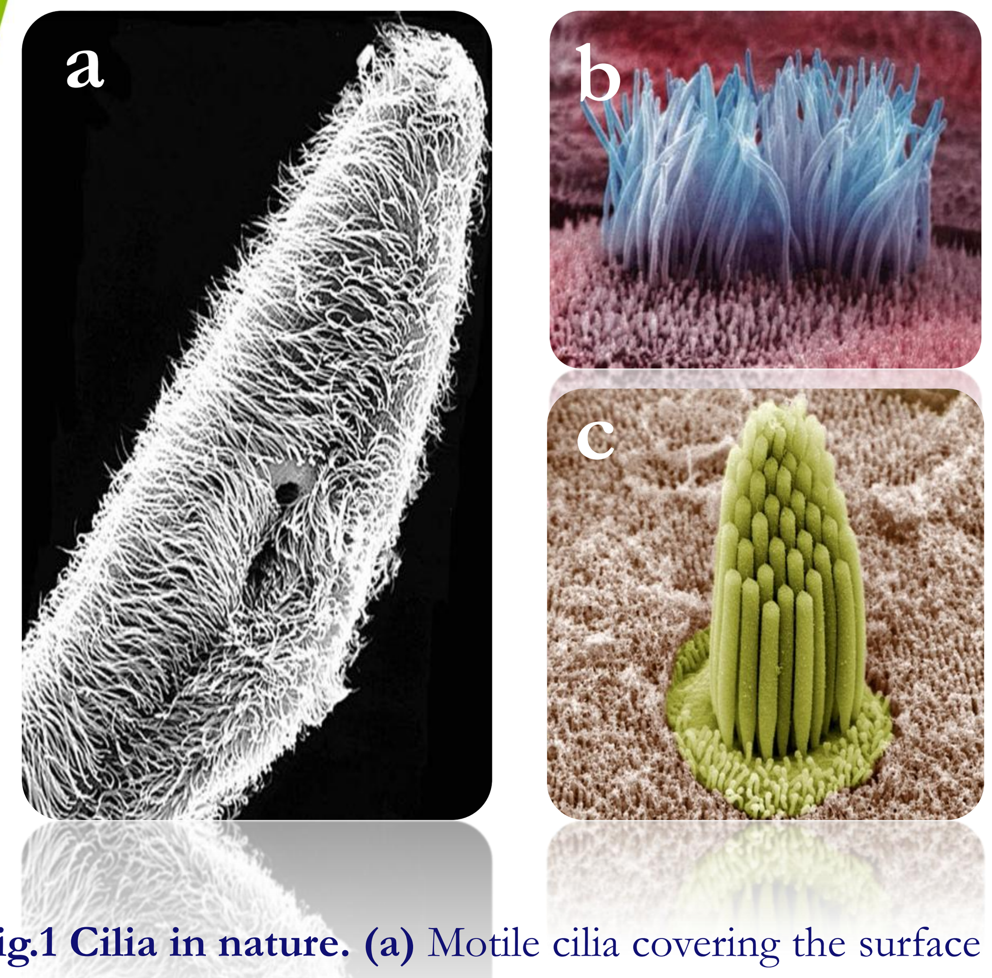

Fig.1 Cilia in nature. (a) Motile cilia covering the surface of paramecium enable swimming; (b) Cilia lining human trachea can expel dust and mucus; (c) Stereo cilia in inner ears enhance acoustic detection.

Introduction and main result

Cilia are microscopic hairs that can be found in nature in a wide range of organisms from protozoa to human beings. They are important for various and vital functions including swimming, transportation and sensing (Fig.1). Mimicking nature, various types of functional artificial cilia were made but their applications were limited partly because of tedious processes and high production costs. In this study we realized the fabrication of magnetic artificial cilia in a filament pullout approach, which is fast, cost efficient and suitable to be implemented in a roll-to-roll process.

Fabrication process

A PDMS film, on which microscopic pillars were patterned by soft-photolithography, was attached to a roll with a fixed rotation axis. The pillars serve as initiation points for the pullout of filaments from a precursor layer.

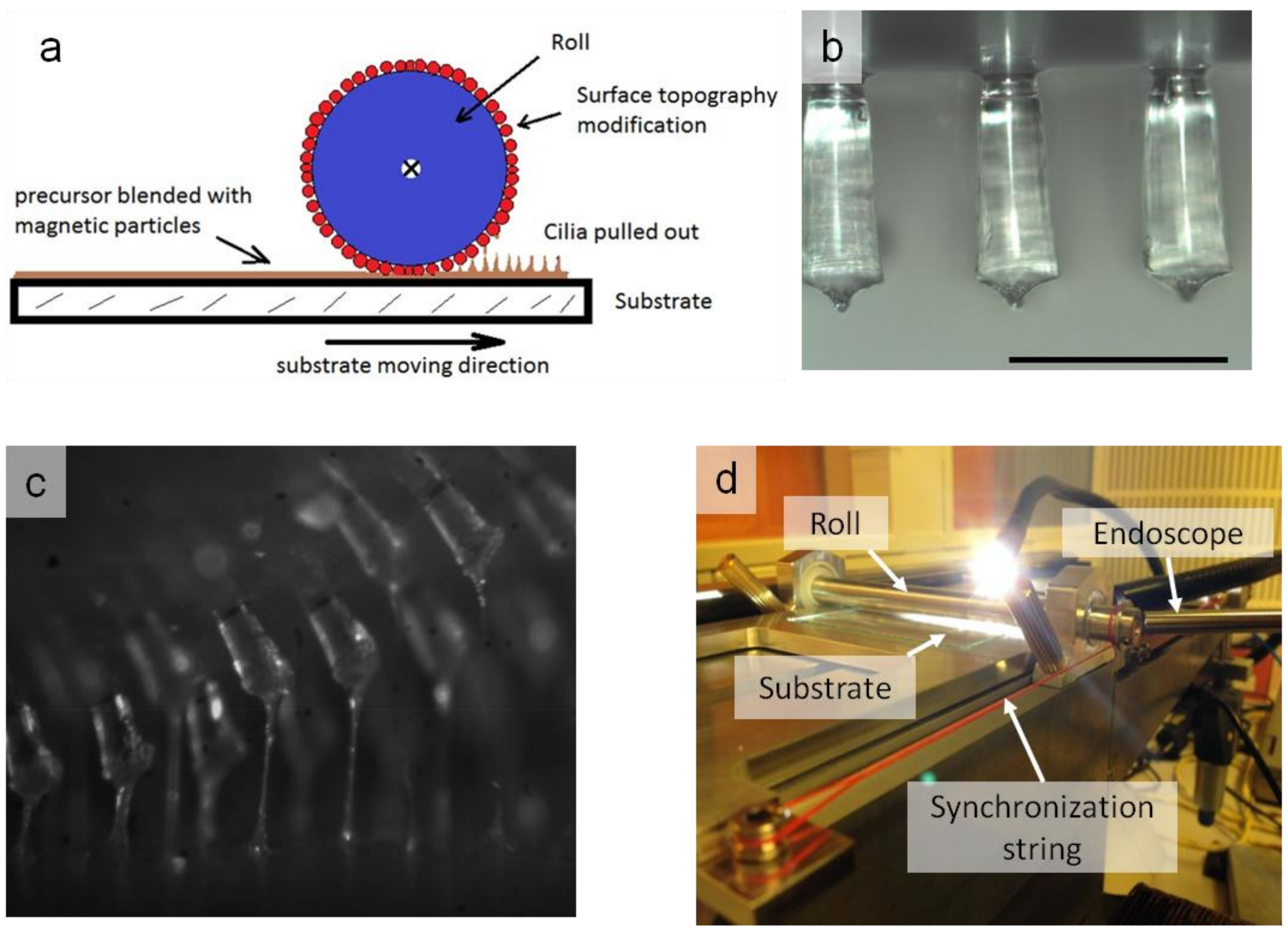

Figure 2: Fabrication process of artificial cilia. (a) The schematic of the fabrication process, the protruded points on the roll partially immerse into the precursor layer and pull out a single thread; during this, a vertical magnetic field of 200 mT is applied; (b) Close-up of the surface modification pillars on the roll, with remaining precursor material on the tips; the scale bar is 1 mm; (c) Snapshot from high speed recording during pull-up process of the filaments; (d) picture of the setup showing the moving parts and the microscope lens.

In order to counter the surface tension which is dominant at such small length scales, we added thixotropy modifiers to a PDMS matrix, thus giving the mixture a high enough yield stress to form free-standing structures after filament breakup. The presence of PDMS-b-PEO copolymer enhances the yield stress originally established by the silica network by orders of magnitude, reaching up to 10^5 Pa.

Table 1: Typical composition of the precursor mixture

	PDMS	Curing agent	Iron microparticles	PDMS-b-PEO copolymer (MW 3000)	Silica nanoparticles
Weight in parts	100	10	50 to 100	15	6 to 20

Analysis and results

Rheological characterization has been carried out under shear conditions in order to obtain quantitative understanding of the precursor properties.

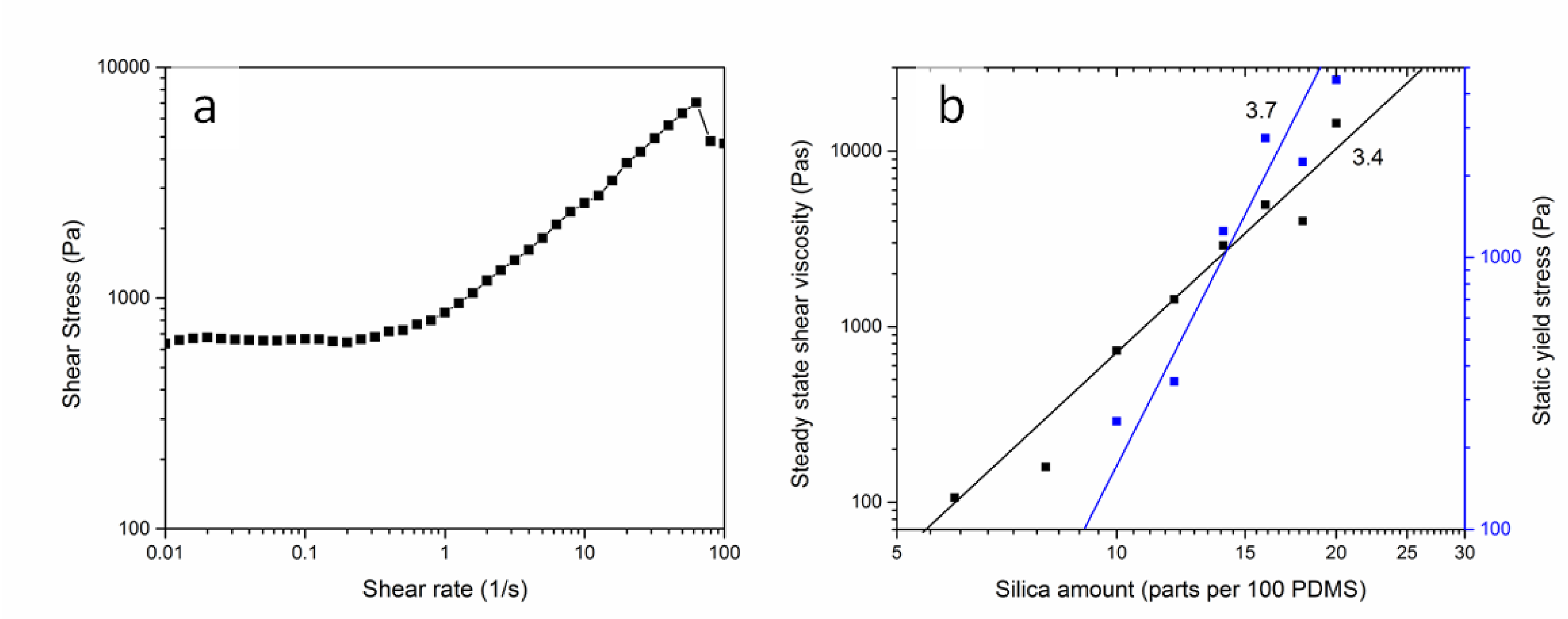

Figure 3: Rheological properties of precursor under shear. (a) A plateau of shear stress at low shear rates indicates a dynamic yield stress, under which the material will not flow; (b) detailed characterization shows the power law dependency of yield stress and viscosity on the amount of silica particles added to the mixture (using composition shown in table 1).

The geometry of the cilia depends not only on the material properties, but also on the pulling process. Parameters such as speed, roll size, pillar size and geometry, immersion depth of the pillars into the precursor and the intensity of the applied magnetic field can all contribute to the final result. Optimization of this process, to create cilia with a high aspect ratio, thus better magnetic response, is currently under way.

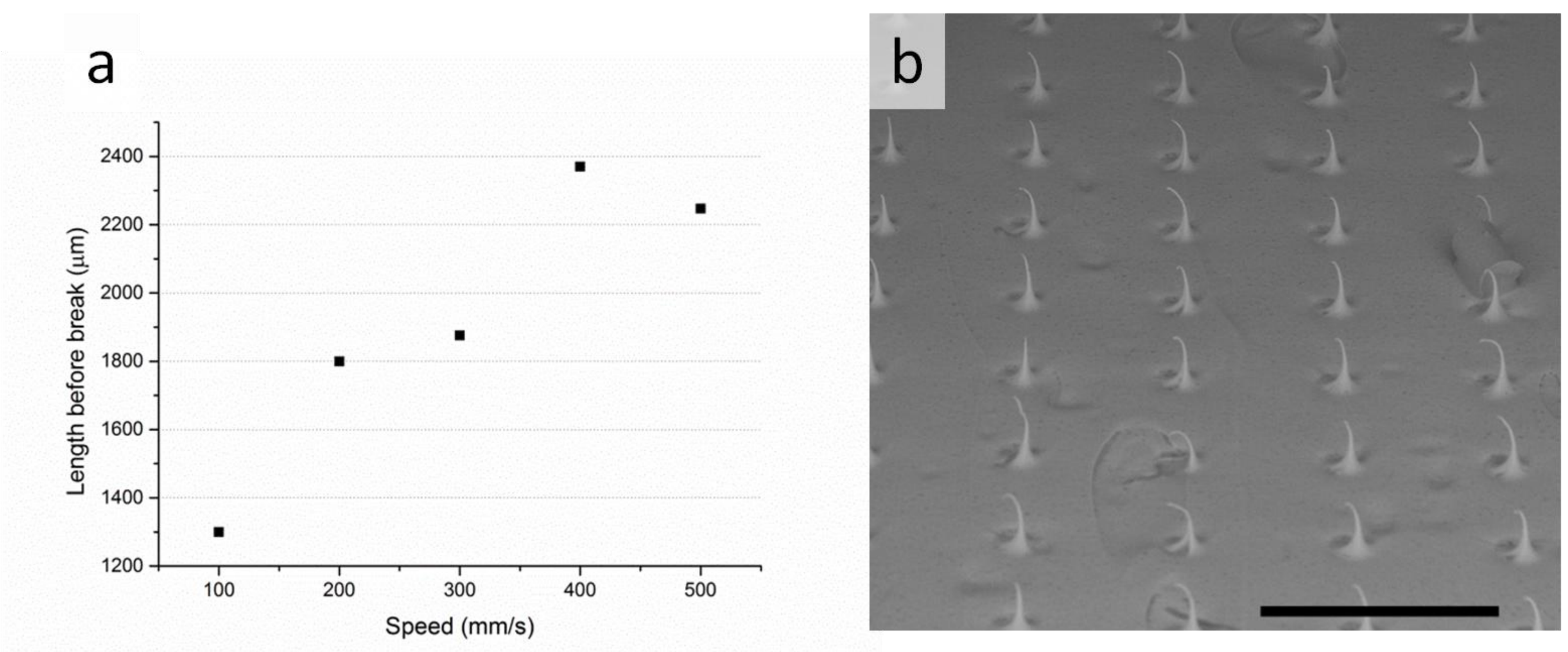

Figure 4: Results from filament pull-out. (a) Example showing that the cilia length is affected by substrate moving speed; (b) SEM picture showing a typical result from the pull-out process; the scale bar is 1 mm.