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Seeing is believing: New insight into structure-mechanics relationships in entangled and crosslinked microtubule networks

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The microtubule cytoskeleton is essential in maintaining the shape, strength and organization of cells and its misregulation has been implicated in neurological disorders and cancers. To better understand the structure-mechanics relationships in microtubule networks, we measure the force-dependent viscoelastic responses of entangled and sparsely crosslinked microtubule networks to precise microscale manipulation. We use magnetic tweezers devices to apply calibrated step stresses and measure the resultant strain as a function of time. At short times the material behaves as an elastic solid. The linear regime is large, with gentle stiffening observed in entangled networks above $\sim$70% strains. Crosslinked networks are stiffer, and show an extended linear regime. At longer times, we find a creeping regime, suggesting that structural rearrangements of the network dominate the mechanical response. To understand the molecular origins of this behavior, we use a newly-developed portable magnetic tweezers device to observe the network morphology using a confocal microscope while simultaneously applying point-like stresses to embedded magnetic particles. We observe substantial network compression in front of the bead with no evidence of long-length scale filament flow, and find that the spatial extent of the deformation field depends sensitively on network architecture and connectivity. Our results are important to understanding the role of the cytoskeleton in regulating cargo transport in vivo, as well as the basic physics of non-affine deformations in rigid rod polymer networks.