Supplementary information

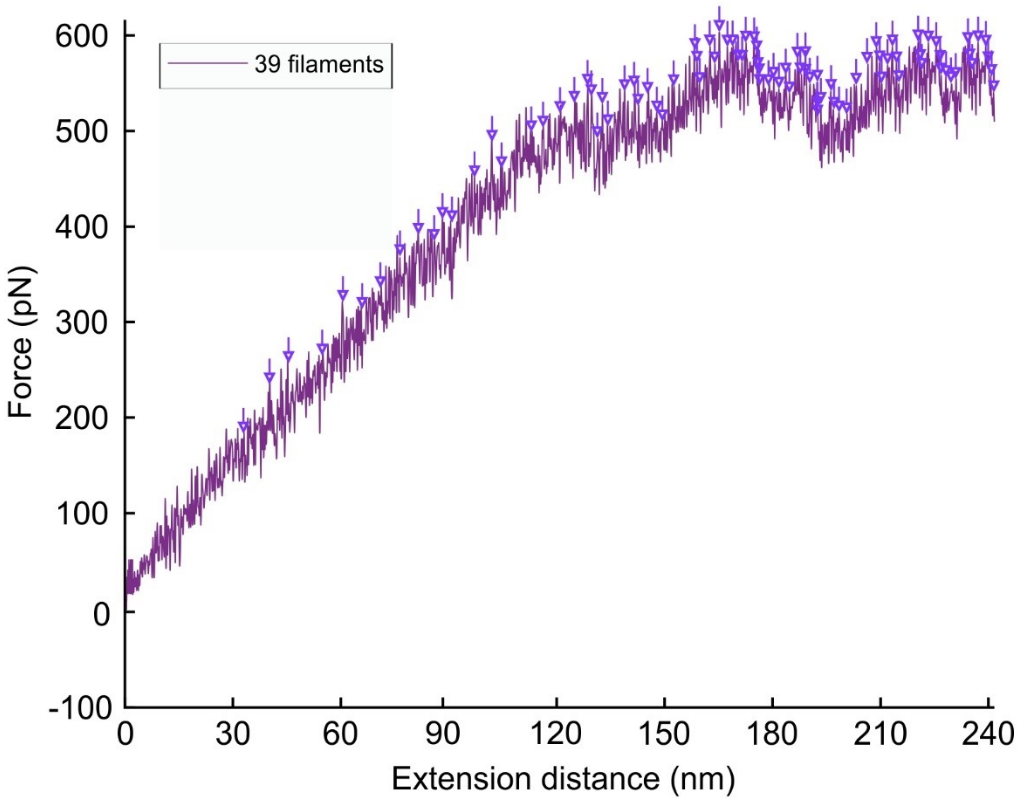

Fig. S1. APMS extension properties at pulling rates of $0.05\ \sigma/t_s$ and the association energy between actin and spectrin end is $0.86\ eV$. The arrows above the force-extension curve indicate when the unfolding of repeats happens.

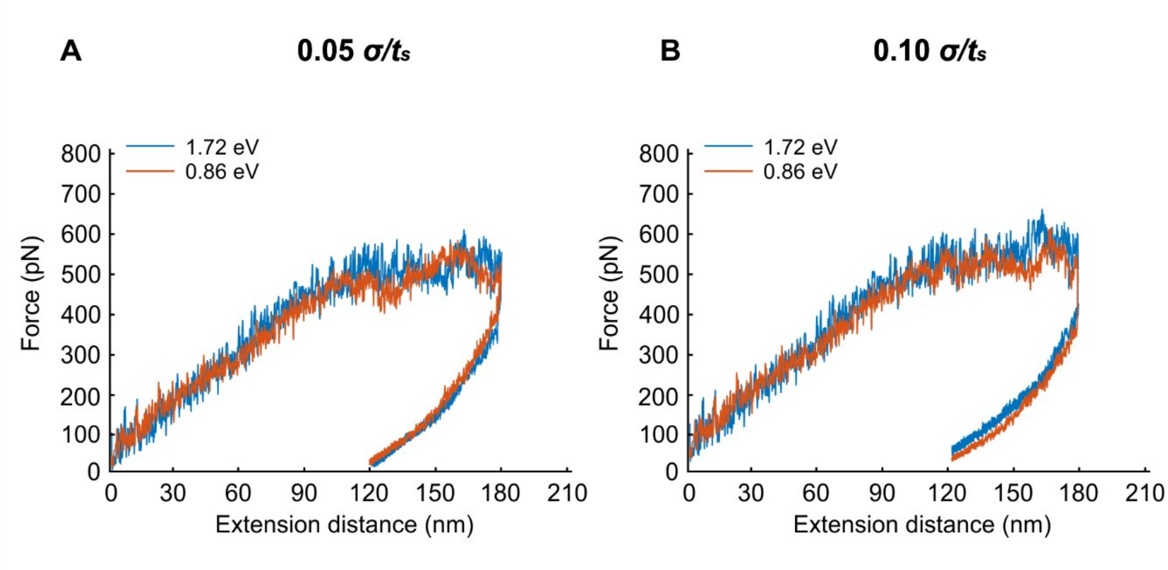

Fig. S2. APMS extension and recovery properties. The simulations were performed at the extension rates of (A) $0.05\,\sigma/t_s$, (B) $0.10\,\sigma/t_s$ and for $0.86\,eV$ and $1.72\,eV$ actin-spectrin association energies. A permanent displacement is observed when the extension force reached its original level during recovery.

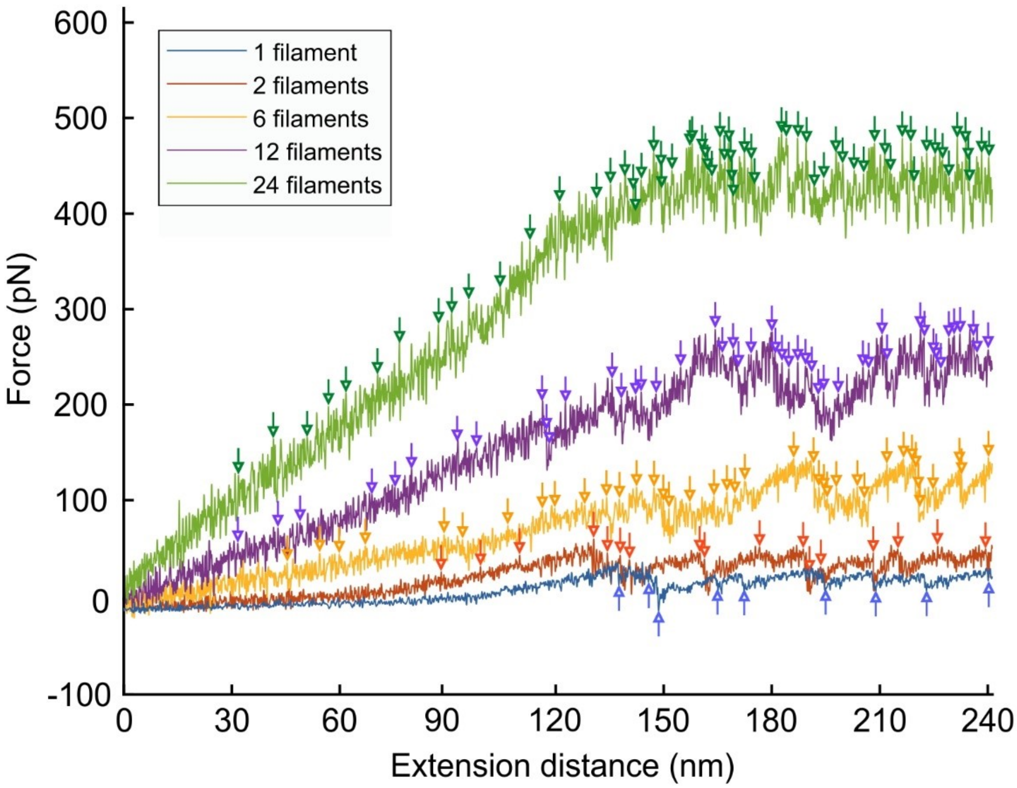

Fig. S3. APMS extension properties when 1, 2, 6, 12, and 24 spectrin filaments are attached to the actin rings and the Langevin equation is implemented. The number of filaments corresponding to the blue line is 1. From the orange line to the green line, the number of filaments varies from 2, 6, $12,$ and 24 respectively, at pulling rates of $0.05\ \sigma/t_s$ and the association energy between actin and spectrin end is $0.86\ eV$. The arrows above or below the force-extension curve indicate when the unfolding of repeats happens.

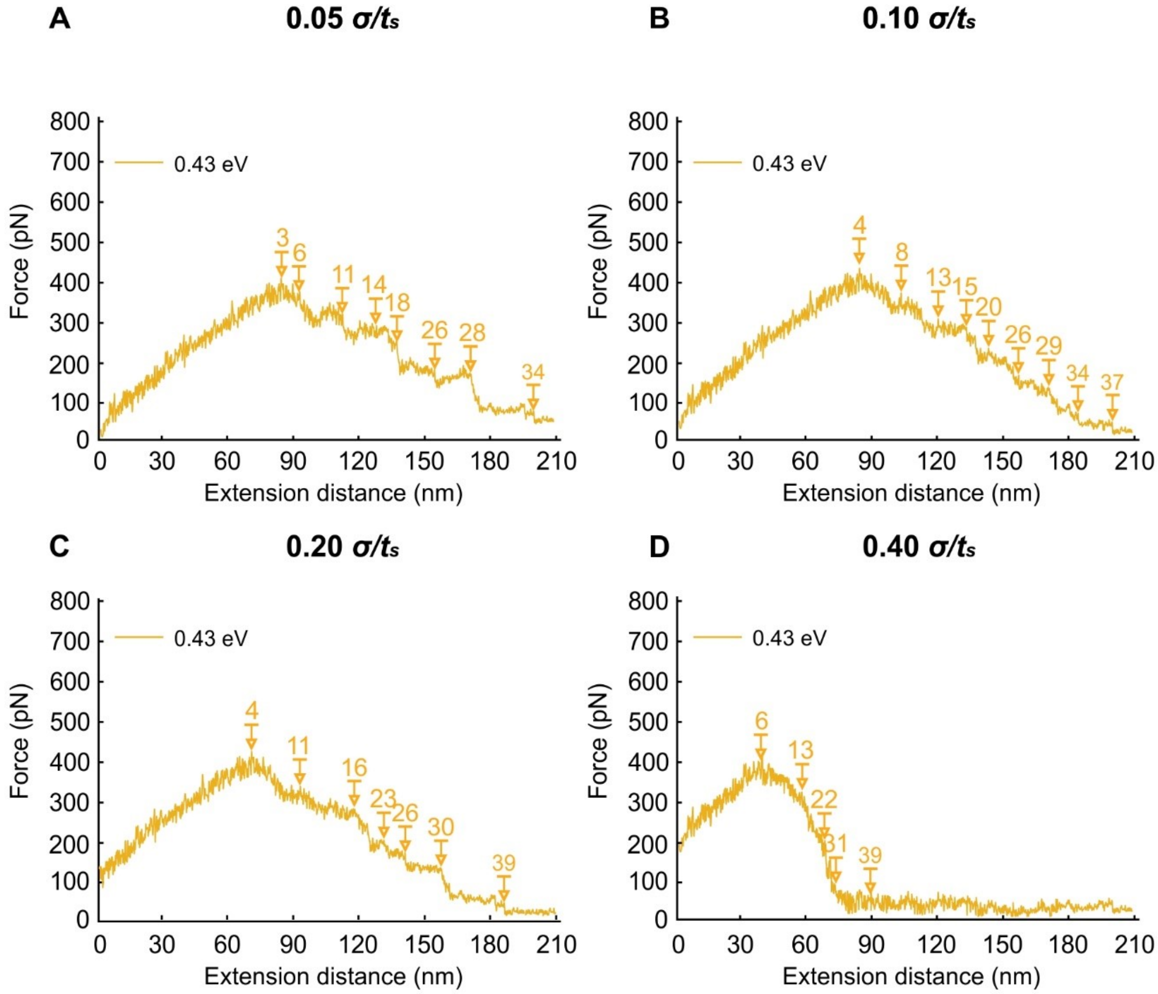

Fig. S4. APMS extension properties under different extension rates. The simulations were performed at the extension rates of (A) $0.05\ \sigma/t_s$, (B) $0.10\ \sigma/t_s$, (C) $0.20\ \sigma/t_s$ and (D) $0.40\ \sigma/t_s$ and at $0.43\ eV$ actin-spectrin association energy. The arrows above the force-extension curve indicate observed dissociations of actin-spectrin junctions. The numbers above the arrows signify the cumulative number of dissociated actin-spectrin junctions at the corresponding extensions.

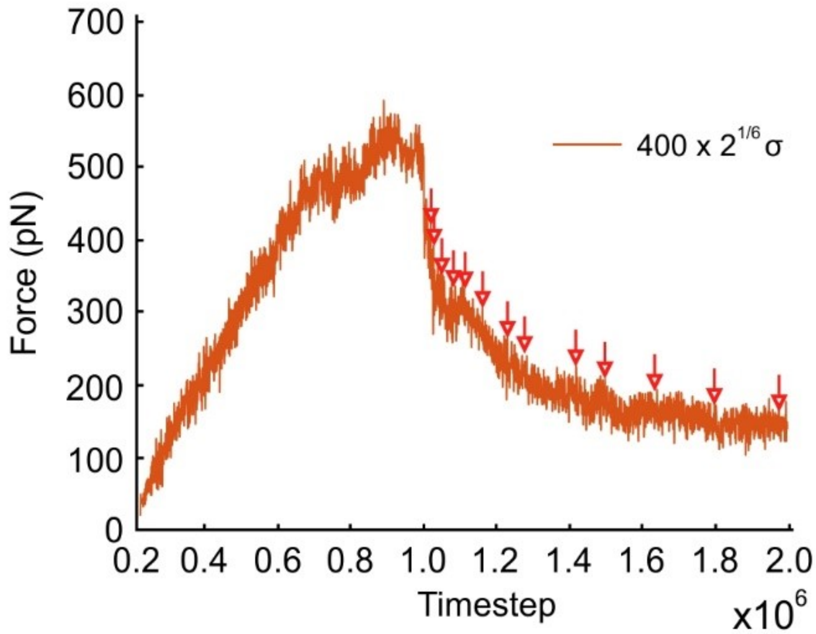

Fig. S5. APMS extensional relaxation properties at pulling rates of $0.05\ \sigma/t_s$. The actin – spectrin association energy is $0.86\ eV$ and the total extension distance is $400 \times 2^{1/6}\sigma$. The arrows above the force-extension curve indicate when a repeat unfolding happens.

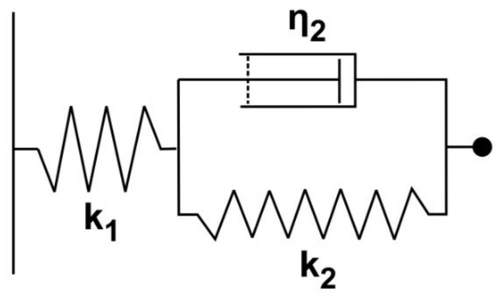

Fig. S6. Mechanical model for the viscoelastic response of APMS to extension and its behavior. The combination of an undamped spring (k_1) in series with an undamped spring (k_2) which is in parallel with a dashpot (η_2) can be used to describe the mechanical response of the APMS.

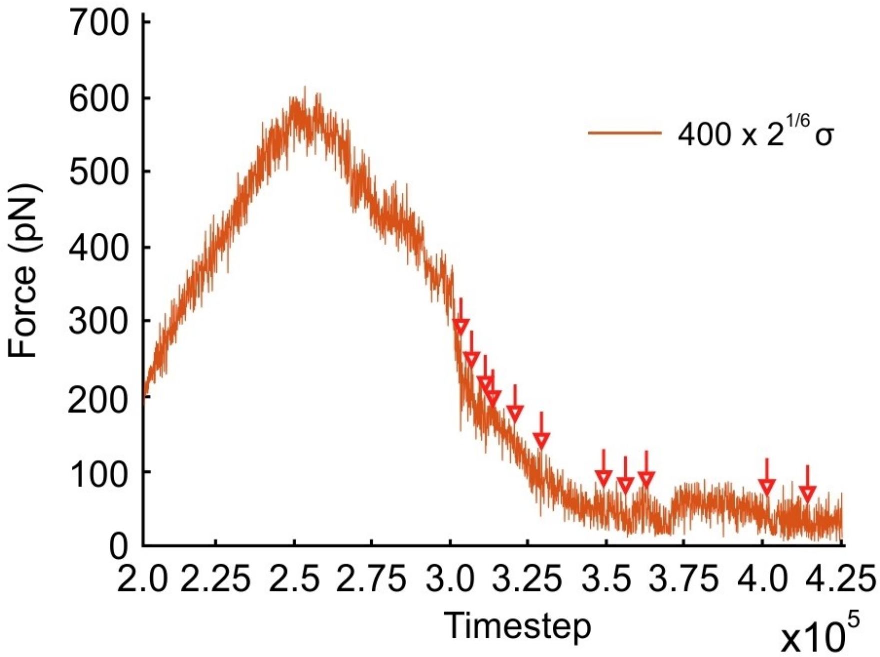

Fig. S7. APMS extensional relaxation properties at pulling rates of $0.40\ \sigma/t_s$**.** The actin – spectrin association energy is $0.86\ eV$ and the extension distance is $400 \times 2^{1/6}\sigma$. The arrows above the force-extension curve indicate when a repeat unfolding happens.

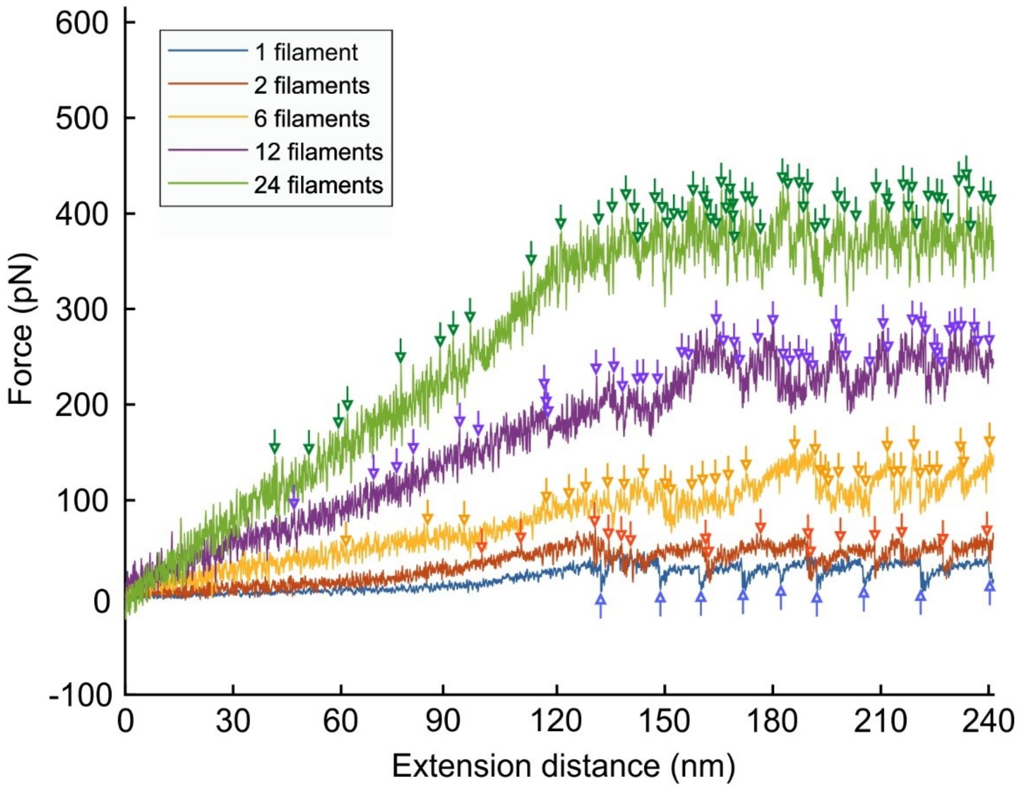

Fig. S8. APMS extension properties when 1, 2, 6, 12, and 24 spectrin filaments are attached to the actin rings and the Langevin equation is not implemented. The number of filaments corresponding to the blue line is 1. From the orange line to the green line, the number of filaments varies from 2, 6, 12, and 24 respectively, at pulling rates of $0.05\ \sigma/t_s$ and the association energy between actin and spectrin end is $0.86\ eV$. The arrows above or below the force-extension curve indicate when the unfolding of repeats happens.

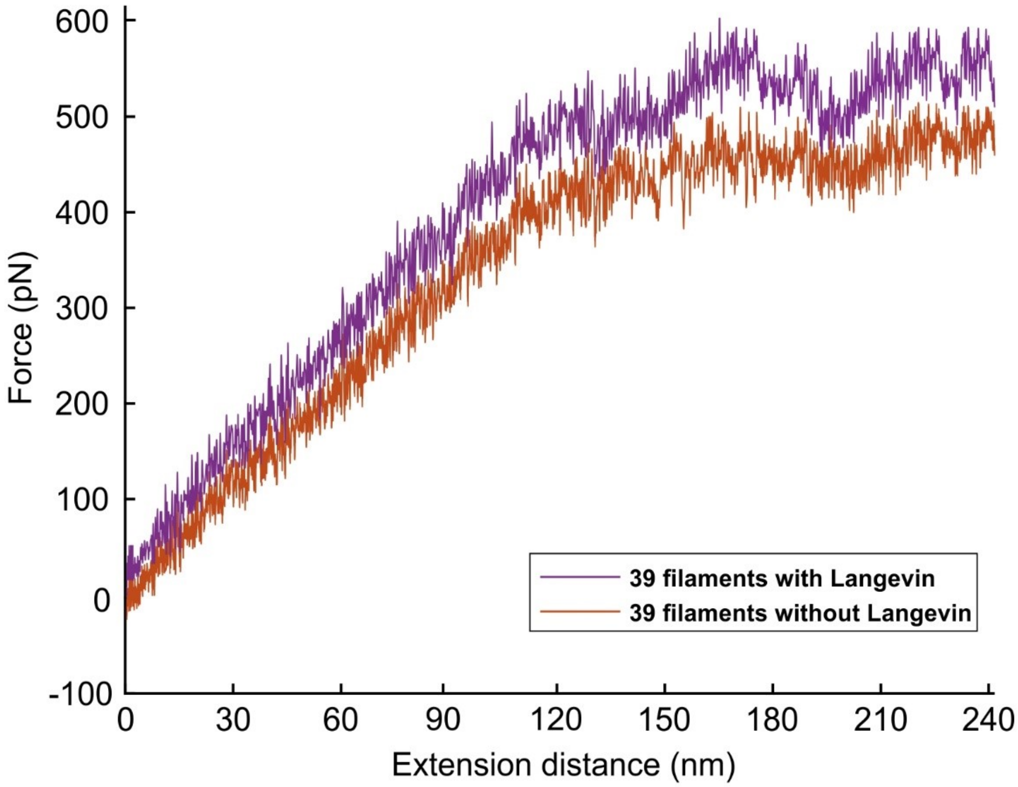

Fig. S9. APMS extension properties when all spectrin filaments (39 filaments) are attached to the actin rings. The purple curve is the force-extension curve when the Langevin equation is implemented. The orange curve is the force-extension curve without implementing the Langevin equation. The pulling rate is $0.05\ \sigma/t_s$, and the association energy between actin and spectrin end is $0.86\ eV$.

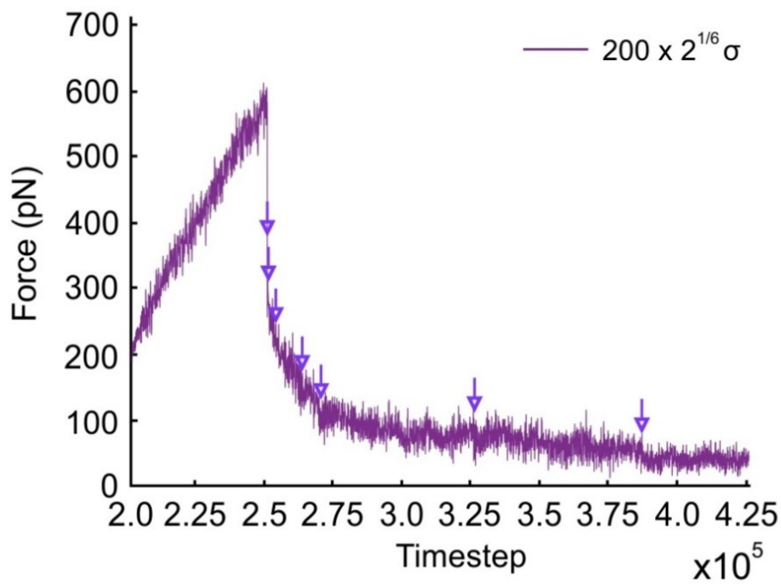

Fig. S10. APMS extensional relaxation properties at pulling rates of $0.40\ \sigma/t_s$. The association energy between actin and spectrin end is $0.86\ eV$ and the extension distance is $200 \times 2^{1/6}\sigma$. The arrows above the force extension curve indicate when the unfolding of repeats happens.

Table S1. Potentials and corresponding parameters used in the model of the axon plasma membrane skeleton

Potentials	Parameters
Actin-Actin	
$U^{AA}_{spring}(r^{AA}_{ij}) = 1/2 k_A (r^{AA}_{ij} - r^{AA}_{eq})^2$	$k_A = 38\ \varepsilon/\sigma^2$ $r^{AA}_{eq} = 2^{1/6} \times 51\sigma$
$U^{AA}_{WCA}\left(r^{AA}_{ij}\right) = 4\varepsilon_{AA}\left[\left(\frac{S_{AA}}{r^{AA}_{ij}}\right)^{12} - \left(\frac{S_{AA}}{r^{AA}_{ij}}\right)^{6}\right] + \varepsilon_{AA}$ **(Eq. 1)**	$\varepsilon_{AA} = 1734\varepsilon$ $S_{AA} = 51\sigma$
$U^{AA}_{b}(\theta) = -\frac{1}{2} k^{AA}_{b} \Delta\theta_{max} ln\left[1 - \left(\frac{\theta - \theta_0}{\Delta\theta_{max}}\right)^2\right]$	$k^{AA}_{b} = 3500\ k_B T$ $\theta_0 \cong 170.77^{\circ}$ $\Delta\theta_{max} = 0.3\ \theta_0$
Actin-Spectrin	
$U^{AS}_{LJ}(r^{AS}_{ij}) = 4\varepsilon_{AS}\left[(S_{AS}/r^{AS}_{ij})^{12} - (S_{AS}/r^{AS}_{ij})^{6}\right] + \varepsilon_{AS}$	$\varepsilon_{AS} = (22/3)\varepsilon$ $S_{AS} = 26\ \sigma$
Spectrin-Ankyrin	
$U^{SK}_{spring}\left(r^{SK}_{ij}\right) = 1/2 k_0 \left(r^{SK}_{ij} - r^{SK}_{eq}\right)^2$	$k_0 = 0.618\ \varepsilon/\sigma^2$ $r^{SK}_{eq} = 2^{1/6} \times 18.75\ \sigma$
$U^{SK}_{WCA}\left(r^{SK}_{ij}\right) = 4\varepsilon_{SK}\left[(S_{SK}/r^{SK}_{ij})^{12} - (S_{SK}/r^{SK}_{ij})^{6}\right]$	$\varepsilon_{SK} = 3.8\ \varepsilon$ $S_{SK} = 18.75\ \sigma$
Actin ring – Actin ring	
$U_{mt} = -\frac{1}{2} k_{mt}\ \Delta d_{max}\ ln\left[1 - \left(\frac{d - d^{RR}_{eq}}{\Delta d_{max}}\right)^2\right]$	$k_{mt} = 19{,}822\ k_B T/d^{RR}_{eq}$ $d^{RR}_{eq} = 185\ nm$ $\Delta d_{max} = 0.3\ d^{RR}_{eq}$

Table S2. Potentials and corresponding parameters used in the model of the spectrin filament

Potentials	Parameters
WCA potential between spectrin beads (Eq. 2)	
$U_{WCA}^{SS}\left(r_{ij}^{SS}\right) = 4\varepsilon_{SS}\left[\left(\frac{S_{SS}}{r_{ij}^{SS}}\right)^{12} - \left(\frac{S_{SS}}{r_{ij}^{SS}}\right)^{6}\right] + \varepsilon_{SS}$	$\varepsilon_{SS} = \varepsilon$
	$S_{SS} = \sigma$
Spectrin bead – Spectrin bead within a virtual ball (Eq. 3)	
$U_{LJ}^{SSB}(r_{ij}^{SSB}) = 4\varepsilon_{SSB}\left[\left(\frac{S_{SSB}}{r_{ij}^{SSB}}\right)^{12} - \left(\frac{S_{SSB}}{r_{ij}^{SSB}}\right)^{6}\right] + \varepsilon_{SSB}$	$\varepsilon_{SSB} = 7.5\varepsilon$
	$S_{SSB} = \sigma$
Segment - Segment in the Repeat (Eq. 4)	
$U_{LJ}^{GG}\left(r_{ij}^{GG}\right) = 4\varepsilon_{GG}\left[\left(\frac{S_{GG}}{r_{ij}^{GG}}\right)^{12} - \left(\frac{S_{GG}}{r_{ij}^{GG}}\right)^{6}\right] + \varepsilon_{GG}$	$\varepsilon_{GG} = (3/4)\varepsilon$
	$S_{GG} = \sigma$
Virtual ball – Virtual ball in a spectrin segment	
$U_{b}^{BB}(\theta) = -\frac{1}{2}k_{b}^{BB}\Delta\theta_{max}\ln\left[1 - \left(\frac{\theta - \theta_0}{\Delta\theta_{max}}\right)^{2}\right]$	$k_{b}^{BB} = 5k_BT$
	$\theta_0 \cong 180^{\circ}$
	$\Delta\theta_{max} = 0.3\ \theta_0$
Spectrin-Spectrin	
$U_{spring}^{SS}(r_{ij}^{SS}) = 1/2k_S(r_{ij}^{SS} - r_{eq}^{SS})^2$	$k_S = 57\varepsilon/\sigma^2$
	$r_{eq}^{SS} = 2^{1/6} \times \sigma$

Table S3. Extension properties of the axon plasma membrane skeleton

Association Energy / Extension Rate	$1.72\ eV$		$0.86\ eV$		$0.43\ eV$		$0.22\ eV$		$0.11\ eV$	
	Rupture	Unfolding	Rupture	Unfolding	Rupture	Unfolding	Rupture	Unfolding	Rupture	Unfolding
$0.05\ \sigma/t_s$	No	YES	No	YES	YES	YES	YES	YES	YES	YES
$0.10\ \sigma/t_s$	No	YES	No	YES	YES	YES	YES	YES	YES	No
$0.20\ \sigma/t_s$	No	YES	YES	YES	YES	YES	YES	No	YES	No
$0.40\ \sigma/t_s$	YES	YES	YES	YES	YES	No	YES	No	YES	No

Table S4. Parameters of the Zener model for $0.05\ \sigma/t_s$ extension rate and $0.86\ eV$ association energy

Parameter (Unit) / Extension Distance (Color)	k_1 (mN / m)	k_2 (mN / m)	η_2 (mNs / m)
$500 \times 2^{1/6}\sigma$ (Blue Curve)	0.954	0.247	0.220
$400 \times 2^{1/6}\sigma$ (Orange Curve)	0.938	0.258	0.240
$300 \times 2^{1/6}\sigma$ (Yellow Curve)	0.908	0.247	0.223
$200 \times 2^{1/6}\sigma$ (Purple Curve)	0.971	0.268	0.136

Table S5. Parameters of the Zener model for $0.40\ \sigma/t_s$ extension rate and $0.86\ eV$ association energy

Parameter (Unit) / Extension Distance (Color)	$k_1\ (mN\ /\ m)$	$k_2\ (mN\ /\ m)$	$\eta_2\ (mNs\ /\ m)$
$400 \times 2^{1/6}\sigma$ (Orange Curve)	0.576	0.062	0.094
$300 \times 2^{1/6}\sigma$ (Yellow Curve)	0.685	0.074	0.137
$200 \times 2^{1/6}\sigma$ (Purple Curve)	1.182	0.101	0.163