

# Current Biology

## Mechanoaccumulative Elements of the Mammalian Actin Cytoskeleton

### Highlights

- $\alpha$ -actinin, filamin, and myosin II paralogs are major mechanoaccumulative proteins
- *Dictyostelium*-developed models predict mammalian paralog-specific mechanoresponses
- Diffusion-mediated accumulation can be separated from myosin II-driven flow
- Cooperativity and catch bonds define a “Goldilocks zone” for mechanoaccumulation

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### In Brief

The actin cytoskeleton controls cellular shape change during normal development and in disease processes. Schiffrhauer et al. discover mammalian cytoskeletal proteins that accumulate in response to stress and outline molecular mechanisms driving this accumulation. These proteins comprise the cell's network-scale response to control cell shape.



# Mechanoaccumulative Elements of the Mammalian Actin Cytoskeleton

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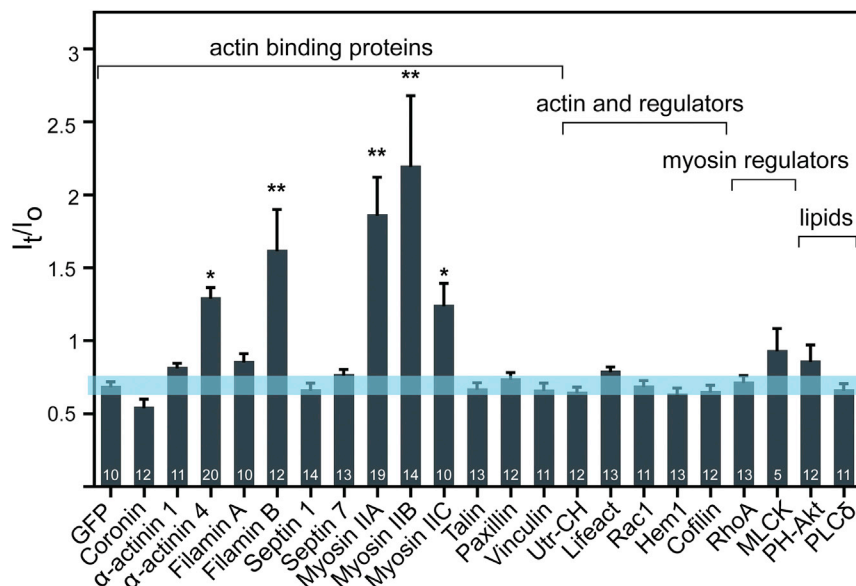
## SUMMARY

To change shape, divide, form junctions, and migrate, cells reorganize their cytoskeletons in response to changing mechanical environments [1–4]. Actin cytoskeletal elements, including myosin II motors and actin crosslinkers, structurally remodel and activate signaling pathways in response to imposed stresses [5–9]. Recent studies demonstrate the importance of force-dependent structural rearrangement of  $\alpha$ -catenin in adherens junctions [10] and vinculin's molecular clutch mechanism in focal adhesions [11]. However, the complete landscape of cytoskeletal mechanoresponsive proteins and the mechanisms by which these elements sense and respond to force remain to be elucidated. To find mechanosensitive elements in mammalian cells, we examined protein relocalization in response to controlled external stresses applied to individual cells. Here, we show that non-muscle myosin II,  $\alpha$ -actinin, and filamin accumulate to mechanically stressed regions in cells from diverse lineages. Using reaction-diffusion models for force-sensitive binding, we successfully predicted which mammalian  $\alpha$ -actinin and filamin paralogs would be mechanoaccumulative. Furthermore, a “Goldilocks zone” must exist for each protein where the actin-binding affinity must be optimal for accumulation. In addition, we leveraged genetic mutants to gain a molecular understanding of the mechanisms of  $\alpha$ -actinin and filamin catch-bonding behavior. Two distinct modes of mechanoaccumulation can be observed: a fast, diffusion-based accumulation and a slower, myosin II-dependent cortical flow phase that acts on proteins with specific binding lifetimes. Finally, we uncovered cell-type- and cell-cycle-stage-spe-

cific control of the mechanosensation of myosin IIB, but not myosin IIA or IIC. Overall, these mechanoaccumulative mechanisms drive the cell's response to physical perturbation during proper tissue development and disease.

## RESULTS AND DISCUSSION

To identify mechanosensitive elements, we examined protein relocalization in response to controlled external stresses applied locally to individual cells. We characterized more than 20 actin-binding, signaling, and lipid-binding proteins by transiently expressing fluorescently tagged constructs in Jurkat T cells (Figure 1), NIH 3T3 fibroblasts (Figure S1A), HeLa (Figure S1B), and HEK293Ts (Figure S1C). Cells were deformed into the pipette by micropipette aspiration (MPA) [12] to a length twice the radius of the pipette ( $2L_p/R_p$ ) for 5 min using a fixed pressure defined by their mechanical properties (Jurkat: 0.075 nN/ $\mu\text{m}^2$ ; NIH 3T3: 0.15 nN/ $\mu\text{m}^2$ ; HEK293T: 0.15 nN/ $\mu\text{m}^2$ ; HeLa: 0.2 nN/ $\mu\text{m}^2$ ). We have previously determined computationally that the tip region in the pipette is the region of highest dilational deformation, whereas the pipette neck experiences shear deformation [13]. The concept of dilation of the cytoskeleton at the tip region is also supported by the immediate decrease in actin density upon deformation by MPA (not shown), similar to what has been observed in red blood cells [14]. Furthermore, although the actin network has a very fast recovery time, a significant immobile fraction exists, which is likely to be the network that experiences these two modes of deformation [15]. Maximal protein accumulation in response to dilational deformation was quantified by normalizing the fluorescence intensity of the cortex in the tip region ( $I_t$ ) to that of the unstressed cortex opposite the pipette ( $I_o$ ) (Figure 1). The blue bar represents the 95% confidence interval for cytosolic GFP quantified in the same manner, a control used in all cell types to denote the threshold over which a protein must accumulate to be significantly mechanosensitive. The response of the majority of proteins fell within this confidence interval, implying their insensitivity toward dilational



**Figure 1. Five Actin-Binding Proteins Respond to an Externally Applied Mechanical Stress**

A ratio ( $I_t/I_o$ ) of maximum tip intensity ( $I_t$ ) to opposite cortex intensity ( $I_o$ ) shows that actin-binding proteins  $\alpha$ -actinin 4, filamin B, myosin IIA, myosin IIB, and myosin IIC accumulated to the highest level among 22 cytoskeletal, signaling, and lipid-binding proteins in Jurkat cells (\* $p < 0.05$ ; \*\* $p < 0.0001$ ). The horizontal blue bar depicts the 95% confidence interval for cytosolic GFP. n values are provided within each individual sample's vertical bar. See also Figure S1 for similar results in 3T3, HeLa, and HEK293T cells.

deformation in all cell types. The greatest accumulative responses were observed in actin-binding proteins, including the myosin IIs. The extent of myosin accumulation did not correlate with the radius of the pipette, ruling out accumulation due to specific local membrane curvature (Figure S2D). In addition, the curvature-sensing protein i-BAR showed no accumulation (Figure S1B), supporting the notion that the observed accumulations are due to mechanical stress sensing rather than curvature sensing. We selected the highly accumulative myosin II,  $\alpha$ -actinin, and filamin for further characterization.

Non-muscle myosin II is an established part of a mechanosensitive system both in *Dictyostelium* and *Drosophila*, where it accumulates at the site of applied forces and drives cellular contraction [9, 12, 13, 16]. The magnitude of accumulation depends on the net force on each myosin II head and requires the presence of actin-crosslinkers to anchor actin filaments [13, 17–19]. Mammalian cells express three paralogs of non-muscle myosin II: IIA (MYH9); IIB (MYH10); and IIC (MYH14). By examining differences in accumulation of these paralogs across multiple cell lines during MPA, we aimed to uncover how the mechanoresponsiveness of this important mechanoenzyme is regulated in mammalian cells. The paralogs have differing duty ratios [19], unique force-dependent affinities to F-actin [20], and distinct spatial distributions in migrating cells [19–22], suggesting non-overlapping roles for the myosin II paralogs. Several studies revealed that cells respond to their mechanical environment by modifying or regulating the expression of these distinct myosin IIs [5, 21, 23, 24].

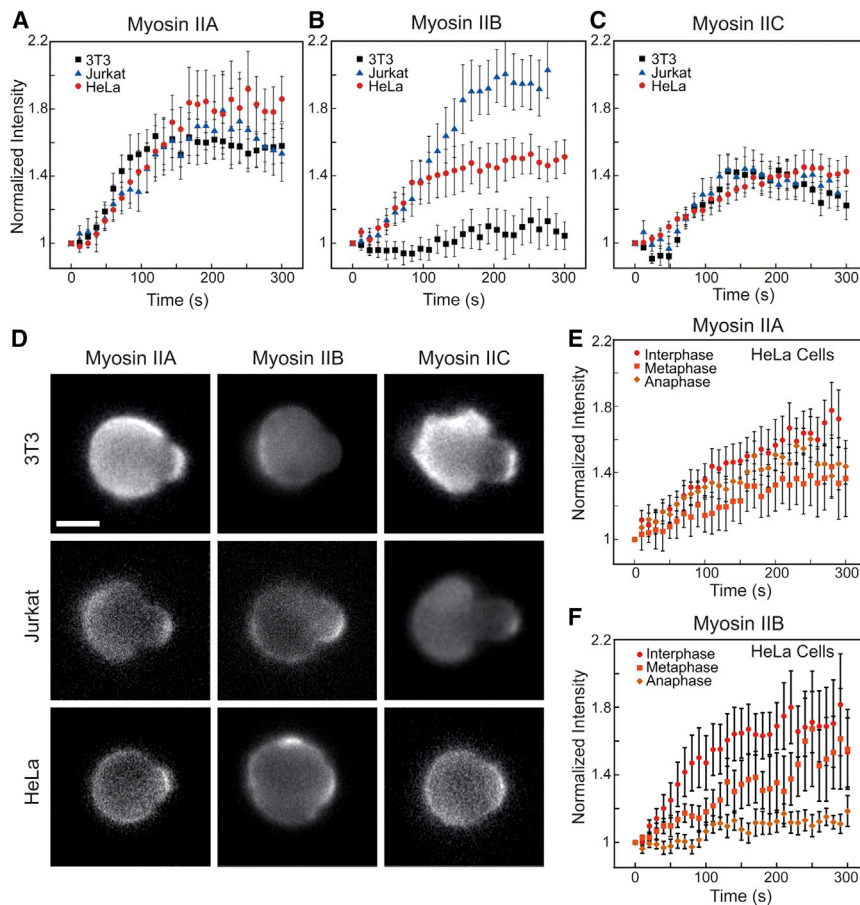
In response to dilational stress, we found myosin IIA and IIC exhibited a characteristic accumulation curve in all cell types, showing a short (30–70 s) delay followed by a sigmoidal rise in protein intensity, plateauing by 150–200 s (Figures 2A and 2C). This biphasic behavior is characteristic of cooperative binding interactions, a behavior we previously modeled for *Dictyostelium* myosin II [25]. The network stress-dependent stalling of myosin II heads in the strongly bound state during the myosin power stroke gives rise to this cooperativity and promotes bipolar thick

filament assembly [9, 13, 18, 26]. Once the accumulated myosin II fully opposes the applied stress, the bound heads do not experience increasing stress, resulting in maximal accumulation [13, 25].

Interestingly, whereas the accumulation kinetics for myosin IIA and IIC were

nearly identical between cell types, myosin IIB showed highly cell-type- and cell-cycle-stage-specific behavior. In Jurkats, myosin IIB was the most-mechanoresponsive paralog, achieving greater than 2-fold normalized intensity relative to the opposite cortex. In HeLa cells, myosin IIB accumulated moderately, whereas in NIH 3T3 cells, no appreciable accumulation was detected (Figure 2B). This difference in accumulation did not correlate with endogenous expression levels (Figure S2B inset) or the cortical tensions of the cell types (Figure S2B). It is unlikely that the accumulation of any paralog can be attributed to co-assembly with another, given the consistent behavior of myosin IIA and IIC in cells endogenously expressing very different quantities of all three proteins. In fact, whereas the mechanoresponse of myosin IIB correlated with IIA expression for these first three cell types, Cos-7 cells, which lack myosin IIA (Figure S2B inset), showed robust myosin IIB accumulation (Figure S2C), demonstrating that IIB's mechanoresponse is independent of IIA. In addition, the accumulation of myosin IIB exceeded that of any other myosin II in Jurkat cells and did not accumulate in 3T3s despite the presence and accumulation of myosin IIA. Further, whereas myosin IIA showed no change in mechanoresponse over the cell cycle in HeLa cells (Figures 2E, S3A, and S3B), the myosin IIB mechanoresponse is cell-cycle-stage specific; it accumulates in interphase and metaphase, but not anaphase (Figures 2F, S3A, and S3B). This cell cycle specificity implicates relatively transient regulatory mechanisms for the myosin IIB mechanoresponse that tune cellular shape change during cytokinesis. One explanation is the phosphoregulation of IIB is distinct from that of IIA and IIC. Indeed, a short serine-rich stretch within the assembly domain of IIB confers its distinct localization pattern and behavior in cells in a phosphorylation-dependent manner [27], and this regulation could also affect myosin IIB mechanoaccumulation.

Force sharing among actin crosslinkers is also important for cellular mechanoresponsiveness [13]. From our search for mechanoresponsive elements, the actin crosslinkers  $\alpha$ -actinin 4 and filamin B strongly responded. Interestingly,  $\alpha$ -actinin 1



**Figure 2. Myosin IIA and IIC Show Mechanoaccumulation in All Contexts Examined, Whereas Myosin IIB Shows Mechanoaccumulation in Distinct Cell Types and Phases of the Cell Cycle**

(A and C) Traces of myosin IIA (A) and myosin IIC (C) accumulation over time (normalized intensity;  $I_t/I_0$ , normalized to time zero) show initial sigmoidal kinetics indicative of cooperativity, followed by a late plateau, a curve which is similar in three distinct cell types: NIH 3T3 fibroblasts; Jurkat T cells; and HeLas ( $n > 10$  cells/trace).

(B) Myosin IIB shows distinct kinetics and levels of mechanoresponsive plateau in the three cell types ( $n > 10$  cells/trace).

(D) Representative images of the maximum accumulation of GFP-labeled myosins shows a similar ratio of tip intensity to opposite cortex intensity for myosin IIA and IIC in all three cells but a very different ratio for myosin IIB (scale bar represents 10  $\mu\text{m}$ ).

(E and F) Myosin IIA (E) behaves similarly between the stages of the cell cycle induced by treatment with STLC (metaphase) STLC+Purvalanol (anaphase), or DMSO (interphase), whereas myosin IIB (F) becomes non-mechanoresponsive in anaphase ( $n > 9$  cells/trace).

See also [Figures S2 and S3](#).

troscopy [FCS] in [Figures S4D–S4F](#), compared to 10  $\mu\text{m}^2/\text{s}$  used in the original model) and longer actin filaments in the mammalian cytoskeleton compared with *Dictyostelium* [28]. To fully recapitulate the experiment, the on and off rates of

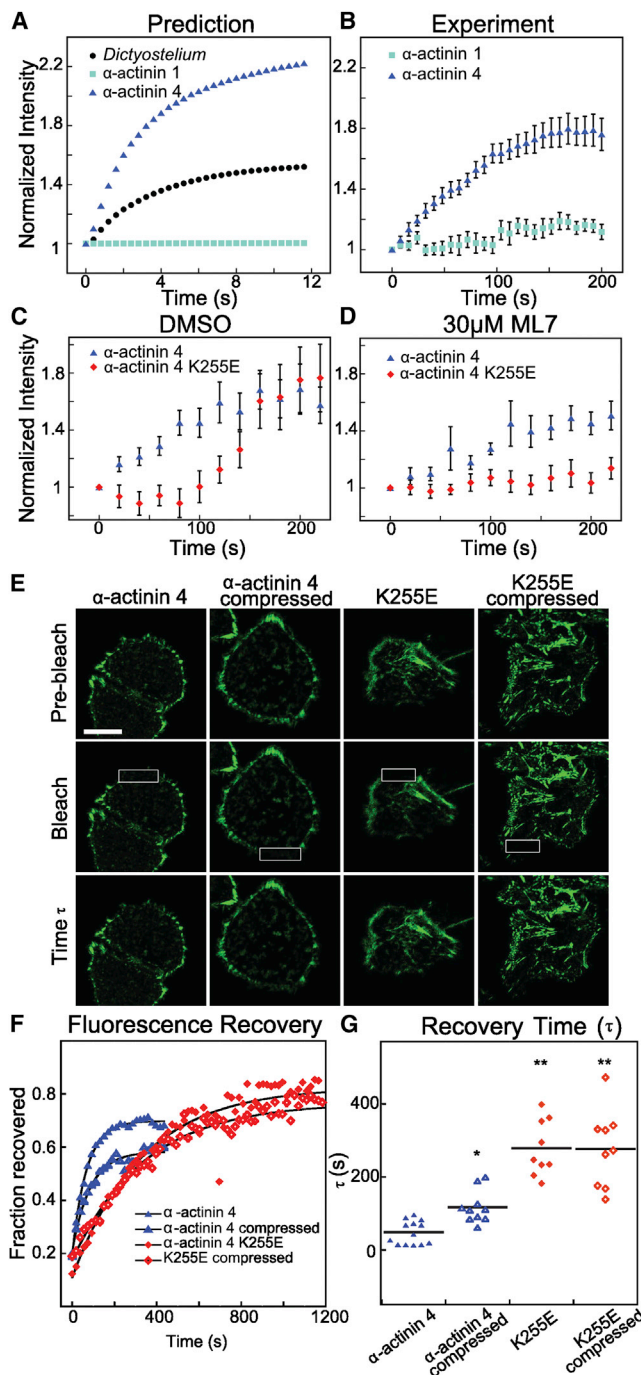
and filamin A did not accumulate significantly in any cell type. Thus, we examined what factors could lead to such paralog-specific differences. We previously characterized the force-dependent accumulation of the *Dictyostelium*  $\alpha$ -actinin and filamin to dilated and sheared regions, respectively [13]. In the absence of myosin II, we determined  $\alpha$ -actinin strongly accumulated to dilated regions of the cell with significantly faster kinetics than myosin II. In contrast, filamin displayed rapid, cooperative, local enrichment in sheared regions at the pipette neck [13].

We modified a reaction-diffusion model first developed for *Dictyostelium*  $\alpha$ -actinin [13] to predict mammalian  $\alpha$ -actinin accumulative behavior ([Figure 3A](#)), by using measured binding affinities for mammalian  $\alpha$ -actinin 1 ( $K_d = 0.36 \mu\text{M}$ ) or  $\alpha$ -actinin 4 ( $K_d = 32 \mu\text{M}$ ) without altering the other parameters ([Table S1](#)). This model assumes the binding lifetime of  $\alpha$ -actinin increases upon the application of force due to catch-bond behavior. Simulations of the model predicted that, owing to intrinsic differences in their initial binding affinities,  $\alpha$ -actinin 4, but not  $\alpha$ -actinin 1, would accumulate in response to deformation ([Figure 3A](#)). During MPA,  $\alpha$ -actinin 4 strongly accumulated in Jurkat cells with a curve shape strikingly similar to those in the simulations, whereas  $\alpha$ -actinin 1 did not accumulate ([Figure 3B](#)). However, the experimentally observed accumulation of  $\alpha$ -actinin 4 was about 25 times slower than in the simulations. This difference is partly explained by a slower  $\alpha$ -actinin rate of diffusion ( $3.7 \pm 0.2 \mu\text{m}^2/\text{s}$  as measured by fluorescence correlation spec-

actin binding had to be slowed 8-fold, suggesting a level of mammalian  $\alpha$ -actinin regulation not seen in *Dictyostelium* ([Figure S4A](#)). Here, through the use of modeling, we showed the initial binding affinity of an actin crosslinker dictates its general mechanoaccumulative behavior. In the model, the rapid accumulation of the lower-affinity  $\alpha$ -actinin 4 is driven by a high rate of exchange with the actin network and a large pool of the unbound species. This dynamic crosslinker exchange can explain the rapid and dramatic changes in localization as the crosslinkers lock onto the network in response to mechanical stress. Further, actin-binding affinity must be low enough for there to be an available pool of crosslinkers for mechanoaccumulation to occur but high enough for the protein to bind; hence, a “Goldilocks zone” of affinity is suggested—not too high, not too low, just right.

To probe the molecular mechanism of  $\alpha$ -actinin catch-bond behavior, we analyzed the  $\alpha$ -actinin actin-binding domain (ABD), which is highly conserved among actin-binding proteins [29]. This domain consists of two calponin homology (CH) domains, each with an actin-binding site, that are normally tethered in a closed conformation by a salt bridge at the CH-CH interface. A mutation of lysine-255 to glutamate (K255E) in  $\alpha$ -actinin 4 disrupts this salt bridge, driving the molecule into a permanently open configuration and revealing a third actin-binding site. In vitro, the K255E mutant has a 5-fold higher actin-binding affinity than the wild-type (WT) protein [30, 31]. We hypothesized that network stress disrupts the salt bridge and converts the protein





**Figure 3. A Force-Dependent Model Based on Actin-Binding Affinity Predicts the Mechanoaccumulative Behavior of  $\alpha$ -Actinins, and the High-Affinity  $\alpha$ -Actinin 4 Mutant K255E Is Non-mechanoresponsive**

(A) A reaction-diffusion catch-bond model of mechanoaccumulation derived from parameters outlined in *Dictyostelium* predicts high accumulation of mammalian  $\alpha$ -actinin 4 and low accumulation of  $\alpha$ -actinin 1 based on published actin-binding affinities.

(B) This prediction captured both the protein behavior and shape of the curve in aspiration experiments in Jurkat cells ( $I/I_0$  normalized to time zero;  $n = 12$  cells/trace).

(C and D) The  $\alpha$ -actinin 4 K255E mutant has a 5-fold higher binding affinity (C) and shows delayed, myosin-dependent (D) accumulation as determined by

into the open, high-affinity conformation, giving rise to catch-bond behavior of WT  $\alpha$ -actinin 4 and leading to localized, stress-dependent accumulation. To test this, we analyzed the mechanoaccumulation kinetics of the K255E mutant, which we hypothesized lacks this mechanosensitive switch. Indeed,  $\alpha$ -actinin 4 K255E did not accumulate in the first 100 s of aspiration. However, the mutant began to accumulate after 100 s (Figure 3C) with accumulation kinetics mirroring those of myosin II (Figure 2). Therefore, we tested the role of myosin II by inhibiting the mechanoreponse of the three myosins with the myosin light chain kinase inhibitor ML7 (Figure S2E). Upon the addition of 30  $\mu$ M ML7, WT  $\alpha$ -actinin 4 protein still accumulated considerably, whereas the K255E mutant did not (Figure 2D). To rule out off-target effects of ML7, we independently verified the result using 10  $\mu$ M Y-27632, an inhibitor of the Rho-associated kinase ROCK, which also regulates myosin light chain phosphorylation. The results were nearly identical for the two inhibitors (Figure S2E). The model predicts that a simple 5-fold change in actin-binding affinity would not prevent  $\alpha$ -actinin 4 accumulation (Figure S4B), suggesting the K255E mutation perturbs  $\alpha$ -actinin's mechanism of mechanoreponse.

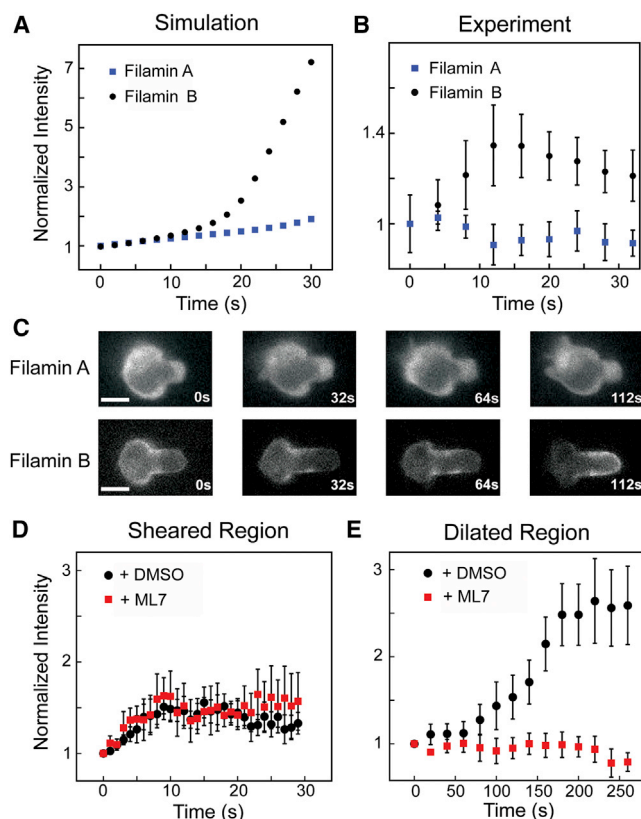
To assess the necessity of the salt bridge for catch bonding, we analyzed the fluorescence recovery after photobleaching (FRAP) of both WT and mutant  $\alpha$ -actinin 4 in HeLa cells in the absence or presence of compressive stress (Figure 3E). Cells were compressed with a thin sheet of agarose, reducing their height by roughly a factor of 2. We have demonstrated previously that this technique drives the accumulation of mechanosensitive proteins, including myosin II and cortactin, to the cell's lateral edges where dilation is highest [13] as the cell actively resists the applied load [15]. Although the exact force felt by the cytoskeleton is difficult to quantify in this technique, the recovery time ( $\tau$ ) of proteins that lock onto the cytoskeleton under physiologically relevant applied loads increases [15]. The K255E mutant localized to stress fibers more readily than the WT even without applied stress, but all FRAP measurements were taken from the cell cortex (Figure 3E). Similar to a previous report [31], the higher-affinity K255E mutant showed much-slower recovery than WT (Figures 3F and 3G). Interestingly, whereas WT  $\alpha$ -actinin 4 showed slower recovery under agarose overlay, the K255E mutant showed no significant change in recovery time ( $\tau$ ) or immobile fraction (Figures 3F, 3G, and S4H). Thus, the catch-bond behavior of  $\alpha$ -actinin 4 is most likely dependent on the conversion of the highly conserved ABD from a closed to an open conformation, a change regulated by the salt bridge. In addition, a late, myosin-dependent cortical flow phase is responsible for moving the higher-affinity K255E mutant to the

using the pan-myosin II inhibitor ML7 at 30  $\mu$ M ( $n > 16$  cells/trace). Myosin accumulation was fully inhibited by ML7 (Figure S2E).

(E) FRAP analysis of HeLa cells expressing GFP- $\alpha$ -actinin 4 and the K255E mutant in normal and compressed state. White boxes show bleached region at the time of bleaching, and "Time  $\tau$ " shows the level of fluorescence for each condition after one e-fold time of recovery as outlined in (G) (scale bar represents 10  $\mu$ m).

(F and G) Representative FRAP traces show a much-faster recovery time for  $\alpha$ -actinin 4 than K255E. The applied stress from agarose overlay drives slower recovery of  $\alpha$ -actinin 4 but no change in K255E recovery (\* $p = 0.001$ ; \*\* $p < 0.0001$ ).

See also Figure S4 and Table S1.



**Figure 4. A Force-Dependent Model Based on Actin-Binding Affinity Predicts the Mechanoaccumulative Behavior of Filamins to a Region of Shear Deformation, Followed by Myosin-Driven Cell Tip Accumulation**

(A) A cooperative reaction-diffusion catch-bond model of mechanoaccumulation predicts low accumulation of filamin A and high accumulation of filamin B to the neck region of the cell, where shear deformation is highest. (B) In Jurkat cells, filamin A does not accumulate appreciably whereas filamin B accumulates to the cell neck, though initial accumulation was followed by a decay phase ( $I_t/I_0$  normalized to time zero;  $n = 10$ ). (C) This decay phase resulted from flow of filamin B, but not filamin A, from the cell neck to the cell tip (scale bars represent 10  $\mu\text{m}$ ). (D) Accumulation to the cell neck was not myosin dependent ( $n = 10$ ). (E) However, flow to the cell tip was myosin II dependent. Cells in (D) and (E) were treated with DMSO or the pan-myosin II inhibitor ML7 at 30  $\mu\text{M}$  ( $n = 12$ ). See also Figure S4 and Table S2.

tip region, a phenomenon we also observed with filamin (see below).

In mammalian cells, non-muscle filamins A and B form Y-shaped dimers, which orthogonally crosslink actin filaments [32]. We previously found that *Dictyostelium* filamin, which forms a similar V-shaped dimer, is sensitive to shear deformation. This sensitivity manifests as an accumulation to the neck of the cell being deformed [13]. The reaction-diffusion model for filamin included cooperativity, predicted robust accumulation of the higher-affinity filamin B ( $K_d = 7 \mu\text{M}$ ), and reduced accumulation of lower-affinity filamin A ( $K_d = 17 \mu\text{M}$ ; Figure 4A). This is in contrast with the stronger accumulation for lower-affinity  $\alpha$ -actinin 4. Whereas both  $\alpha$ -actinin (non-cooperative) and filamin (cooperative) models unveil a Goldilocks zone for which the  $K_d$  is optimal for accumulation, the  $K_d$  that allows the most-robust

accumulation for each protein depends on whether cooperativity is present (Figures S4B and S4C).

We were initially surprised to find that mammalian filamin B accumulated at the tip of the cell in our studies in Jurkats, instead of the neck region. Upon closer analysis, we noted that, within 15 s of the pressure application, filamin B accumulated to the aspirated cell neck (Figure 4B). The kinetics of this accumulation showed acceleration (Figure 4B), suggesting cooperativity exists between neighboring actin-bound filamin B molecules. Longer-term tracking revealed that filamin B flows from the neck to the tip of the cell along the cortex (Figures 4C and 4E), a process not observed in *Dictyostelium*. Filamin A failed to respond to applied pressure (Figures 4B and 4C). Because the timescale for the tip accumulation of filamin B is  $\sim 80$  s (Figure 4E), along myosin II's timescale, we hypothesized that filamin B accumulation in the tip was driven by myosin II accumulation. Upon the addition of 30  $\mu\text{M}$  ML7 or 10  $\mu\text{M}$  Y-27632 (Figure S2E), filamin B showed normal neck accumulation (Figure 4D) but did not accumulate to the tip (Figure 4E). It has been shown that a filamin A mutant lacking the hinge 1 region fails to cause strain stiffening induced by its WT counterpart [33]. However, in our experiments, the filamin B hinge mutant showed WT mechanoaccumulation to either the neck or the tip of the cell (Figure S4I), indicating shear-force sensation does not depend on this hinge. Thus, filamin B shows both rapid, intrinsic, shear deformation-sensitive accumulation at the cell neck, as well as myosin II-dependent cortical flow to the tip of the cell upon applied force. This myosin-dependent cortical flow resembles that seen in the  $\alpha$ -actinin 4 K255E mutant; these two proteins have similar affinities for actin ( $K_d \approx 7 \mu\text{M}$ ), which may allude to the requirement of a specific actin-binding affinity in order to be acted upon by the myosin-dependent flow. In HeLa cells, the important cytokinesis-regulator anillin also responds to the tip of the pipette but does so exclusively during anaphase in a myosin-dependent manner (Figures S3D–S3F). This implies a biological role for myosin-dependent accumulation in mammalian cytokinesis. These myosin-driven cortical network flows are similar to those essential for proper asymmetric cell division during *C. elegans* development [34].

In this study, we uncovered mammalian mechanosensors that accumulate under mechanical stress. We identified a Goldilocks zone of actin-binding affinities, determined by their cooperative or non-cooperative binding properties, which dictates the maximal accumulation of these elements. We discovered two distinct modes of force-dependent accumulation: a rapid, diffusion-based mode dependent on molecular catch-bonding behavior and a slower, myosin-II-dependent cortical flow, which drives actin-binding proteins to the cell tip. We also discovered the cell-type- and cell-cycle-specific mechanosensitivity of myosin IIB, which is intriguing in light of studies implicating myosin IIB as a driver of breast cancer metastasis [35]. As growing evidence demonstrates that cell behavior is modulated by the mechanical properties of the actin network, the molecular mechanisms of the mechanoresponsive cytoskeletal elements involved become critical to understand. For example, mechano-transducing stress fibers, which dynamically form and dissolve during cell migration, are crosslinked largely by  $\alpha$ -actinins and therefore could become more stable via  $\alpha$ -actinin catch-bonding under load [36, 37]. In addition to genetic diseases related to

filamin B and  $\alpha$ -actinin 4 mutations [38, 39], increased expression of the mechanosensitive paralogs of  $\alpha$ -actinin and filamin are strong negative prognosticators in multiple metastatic cancers [40–42]. Defining the mechanisms by which individual proteins and the network as a whole respond to force, and determining which cytoskeletal elements are mechanosensitive is essential for elucidating normal mechanosensitive biological processes and identifying new targets for inhibiting aberrant processes in disease states.

## EXPERIMENTAL PROCEDURES

Experimental procedures include cell culture and transfection, live-cell fluorescence imaging, MPA, FRAP, FCS, drug treatments, and computational modeling. Tables of model parameters are provided in Tables S1 and S2. All statistical analysis was performed using KaleidaGraph (Synergy Software). Significance of difference was determined using ANOVA with a Fisher's least significant difference (LSD) post-test. The full details of methodology and materials can be found in the Supplemental Experimental Procedures.

## SUPPLEMENTAL INFORMATION

Supplemental Information includes four figures, two tables, and Supplemental Experimental Procedures, and can be found with this article online at <http://dx.doi.org/10.1016/j.cub.2016.04.007>.

## AUTHOR CONTRIBUTIONS

E.S.S., T.L., E.R.G., V.S., and D.N.R. conceived the experiments. E.S.S., T.L., V.S., and X.Q. performed the experiments. K.M. and P.A.I. developed the model and carried out the simulations. E.S.S. and T.L. wrote the manuscript. V.S., K.M., E.R.G., P.A.I., and D.N.R. edited the manuscript.

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## **Supplemental Information**

### **Mechanoaccumulative Elements of the Mammalian Actin Cytoskeleton**

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Supplemental Information

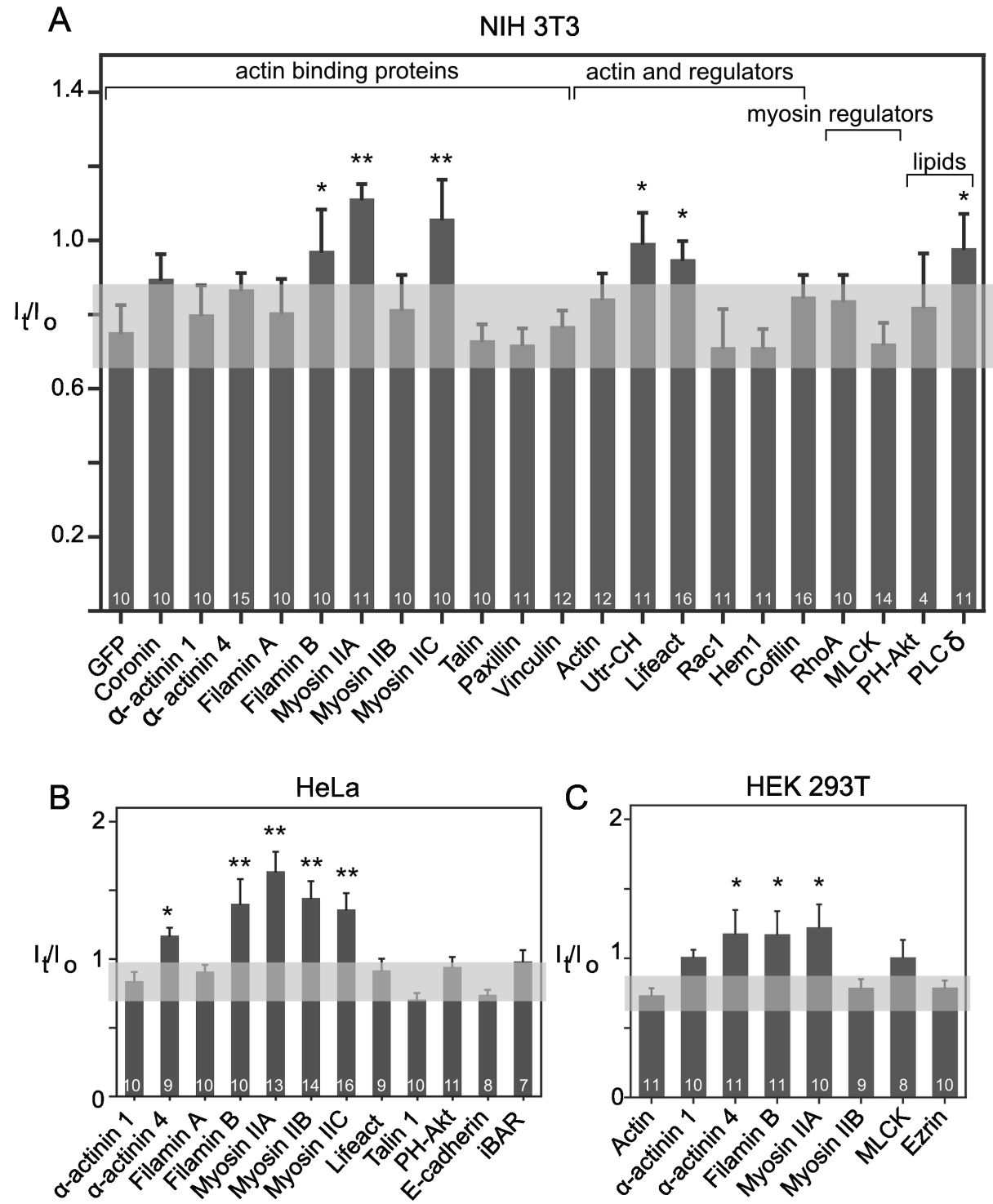


Figure S1

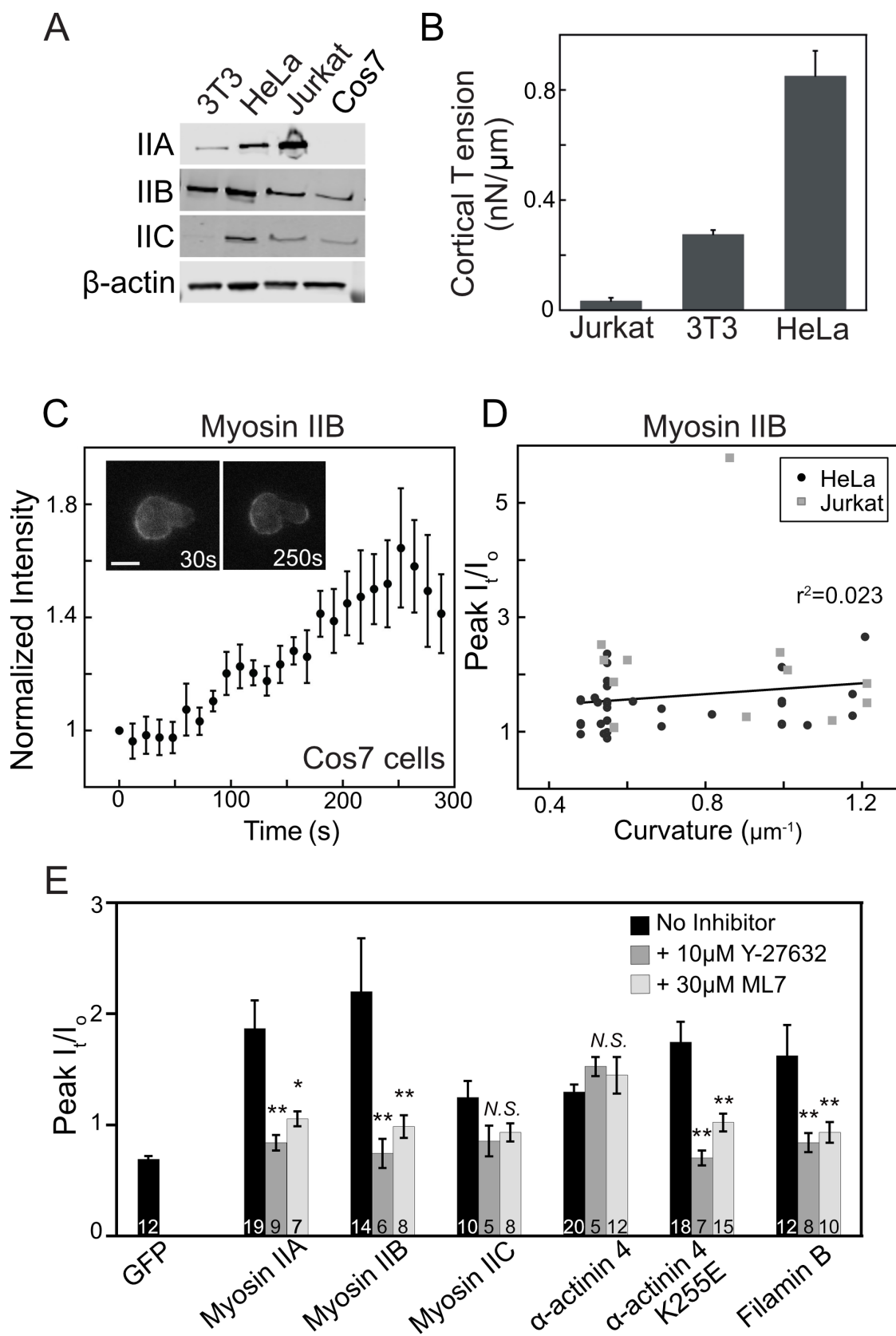


Figure S2

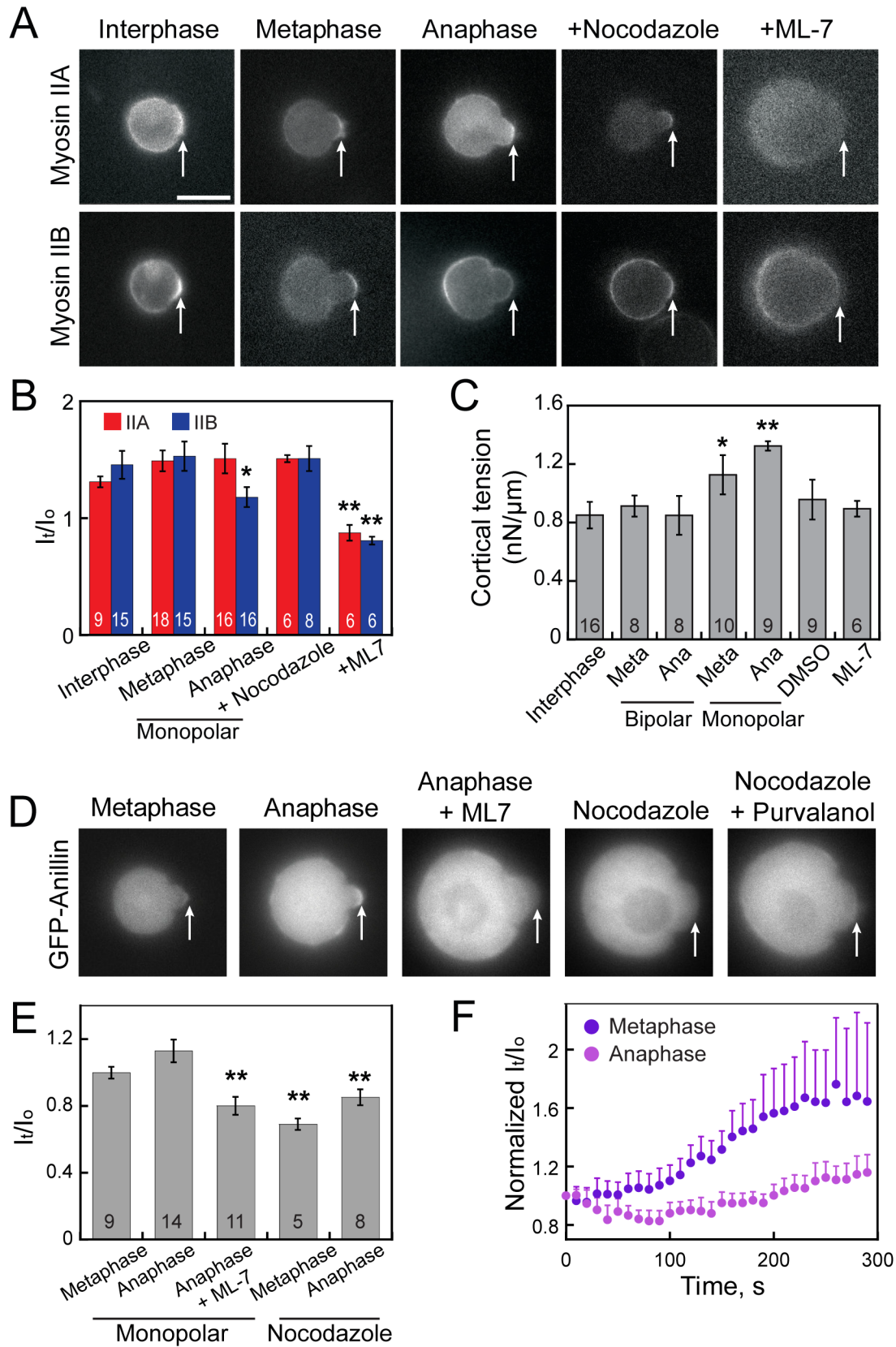


Figure S3



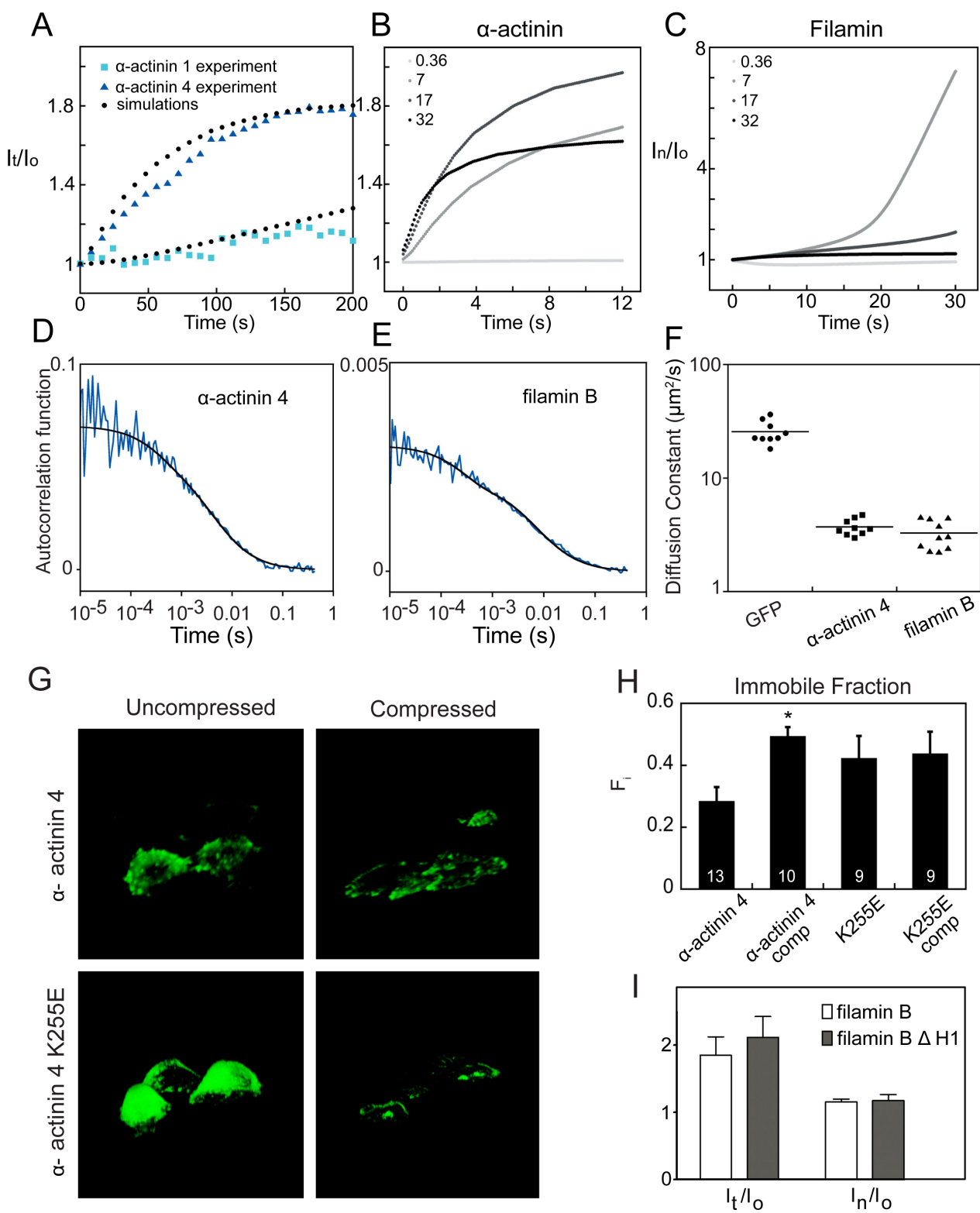


Figure S4

## Figure Legends

### Figure S1. Actin-binding proteins respond most-strongly to externally-applied mechanical stress.

**Related to Figure 1.** (A) In NIH 3T3 cells, (B) HeLa cells, and (C) HEK 293T cells,  $\alpha$ -actinin 4, filamin B, and myosins IIA and IIC showed the most robust accumulation. The peak accumulation of myosin IIB varied between cell types (n values noted on bars, \* $p < 0.05$ , \*\* $p < 0.005$ ). The same trends hold for Jurkat cells (Fig. 1).

### Figure S2. Myosin IIB mechanoresponse is not dependent on endogenous expression or myosin IIA mechanoresponse. Related to Figure 2.

(A) Neither the endogenous expression of the three myosin II paralogs, (B) nor the resting cortical tension of Jurkat, NIH 3T3, and HeLa cells correlate with myosin IIB mechanoresponse (Fig. 2B). Because Cos-7 cells do not express myosin IIA (A), yet show robust myosin IIB accumulation to the tip (n=7) (C), myosin IIA expression is not required for the myosin IIB mechanoresponse. (D) The curvature of the cortex at the tip of cells was estimated as  $2/r$ , where  $r$  is the radius of the pipette used for MPA. Curvature was then plotted against the peak accumulation of myosin IIB ( $I_t/I_o$ ), demonstrating no correlation between curvature and myosin IIB accumulation at the tip. (Fig. 2B). (E) ML7 and Y-27632 treatments inhibit the peak tip accumulation (normalized to the intensity at the opposite side of the cell ( $I_t/I_o$ )) of myosin IIA, myosin IIB,  $\alpha$ -actinin 4 K255E, and Filamin B, but not wild-type  $\alpha$ -actinin 4, in Jurkat cells (\* $p < 0.005$ , \*\* $p < 0.0001$  for inhibitor values compared to “No Inhibitor” values). While myosin IIC accumulated significantly in the absence of inhibitor compared with GFP ( $p < 0.05$ , see Fig. 1), it did not accumulate significantly in the presence of ML7 ( $p = 0.40$ ) or Y-27632 ( $p = 0.62$ ).

### Figure S3. Mechanoresponsiveness of myosin II and anillin in HeLa cells. Related to Figure 2.

(A) Representative micrographs of micropipette aspiration on HeLa cells transiently expressing GFP-myosin IIA or IIB. Nocodazole treatment induces metaphase arrest so these cells are also in metaphase. (Scale bar = 10  $\mu$ m). (B) Average ratio of GFP-myosin II mean intensity at the tip to that at the opposite cortex for aspirated HeLa cells. (C) Cortical tension measurements using micropipette aspiration for interphase and mitotic HeLa cells. DMSO and ML7 measurements were performed on interphase cells. (D) Representative micrographs of micropipette aspiration on HeLa cells stably expressing GFP-anillin. (E) Average ratio of GFP-anillin mean intensity at the tip to that at the opposite cortex. (F) Kinetic traces for anillin’s mechanosensitive accumulation (normalized to  $t = 0$  s) in monopolar mitotic cells. n value is listed on bars; n for each kinetic trace is the same as listed on corresponding bar in (E) (\* $p < 0.05$ , \*\* $p < 0.005$ ).

### Figure S4. Modeling and measuring the mechanisms of filamin and $\alpha$ -actinin mechanoresponse.

**Related to Figures 3 and 4.** (A) The simulations for  $\alpha$ -actinin 1 and  $\alpha$ -actinin 4 match the experimentally observed accumulation curve when the on and off rates are slowed by a factor of 8, preserving each protein’s  $K_d$ . (see Fig. 3B). (B) For both  $\alpha$ -actinin and (C) filamin, a catch-bond model predicts poor accumulation at very high binding affinities ( $K_d = 0.36 \mu$ M), presumably due to a lack of free monomer in the cytoplasm. (B) The  $K_d$  of  $\alpha$ -actinin 4 ( $32 \mu$ M) predicts robust accumulation in the non-cooperative  $\alpha$ -actinin model, (C) but poor accumulation in the cooperative filamin model. The  $K_d$  of filamin B and  $\alpha$ -actinin 4 K255E ( $7 \mu$ M) predicts accumulation in both models. (C) The  $K_d$  of filamin A ( $17 \mu$ M) predicts no accumulation in the filamin model. Thus, both very high and very low  $K_d$  values can inhibit filamin’s mechanoaccumulation; the  $K_d$  at which the most robust accumulation occurs depends on whether the model is non-cooperative ( $\alpha$ -actinin, Fig. 3B) or cooperative (filamin, Fig. 4B) (D) Representative correlation curve measured by FCS for  $\alpha$ -actinin 4 in Jurkat cells and (E) filamin B in HeLa cells. (F) Measured diffusion constants for GFP ( $26 \pm 2.0$ ),  $\alpha$ -actinin 4 ( $3.7 \pm 0.20$ ), and filamin B ( $3.3 \pm 0.30$ ). (G) Rotated view of a 3D projection of HeLa cells, which are flattened to an approximate height of 2  $\mu$ m when compressed with a sheet of 1% agarose 0.2 mm thick for Fig. 3E-G. (H) Compressed  $\alpha$ -actinin 4 showed a higher immobile fraction (\* $p = 0.007$ ), while there was no significant difference between the immobile

fraction of the K255E mutant with and without compression (n values noted on bars). **(I)** A mutant lacking the hinge region of filamin B did not show a difference in accumulation to the tip ( $I_t/I_o$ ) or the neck ( $I_n/I_o$ ) of the aspirated Jurkat cell (n=9).

**Table S1. Parameters for  $\alpha$ -actinin modeling. Related to Figure 3.**

Parameter	Value	Reference
$[F_1]$	72 $\mu\text{M}$	[S1]
$[F_2]$	8 $\mu\text{M}$	[S2]
$D_1$ (ACTN)	3.7 $\mu\text{m}^2\text{s}^{-1}$	Measured
$D_{2,3}$ (cortex)	$D_1/50$	Calculated using parameters outlined in [S2]
$D_{2,3}$ (cytoplasm)	$D_1$	Calculated using parameters outlined in [S2]
$K_D$	0.36 $\mu\text{M}$ (ACTN1), 7 $\mu\text{M}$ , 17 $\mu\text{M}$ , or 32 $\mu\text{M}$ (ACTN4)	[S3] [S4] [S5] [S6]
$k_{\text{on } 1,2}^0$	1.1 $\mu\text{M}^{-1} \text{s}^{-1}$	[S7]
$k_{\text{off } 1,2}^0$	0.4 $\text{s}^{-1}$ (ACTN1), 7.7 $\text{s}^{-1}$ , 19 $\text{s}^{-1}$ , or 35 $\text{s}^{-1}$ (ACTN4)	[S3] Calculated from $K_D$ Calculated from $K_D$ Calculated from $K_D$



**Table S2. Parameters used in filamin model simulations. Related to Figure 4.**

Parameter	Value	Reference
$[F_1]$	100 $\mu\text{M}$	[S8]
$[F_2]$	5 $\mu\text{M}$	[S12]
$D_1$ (filamin)	3.3 $\mu\text{m}^2\text{s}^{-1}$	Measured
$D_2$ (cortex)	0.03 $\mu\text{m}^2\text{s}^{-1}$	[S2]
$D_3$ (cortex)	0.003 $\mu\text{m}^2\text{s}^{-1}$	[S2]
$D_{2,3}$ (cytoplasm)	$D_1$	
$K_D$	0.36 $\mu\text{M}$ , 7 $\mu\text{M}$ (FLNA), 17 $\mu\text{M}$ (FLNB), or 32 $\mu\text{M}$	[S3] [S4] [S5] [S6]
$k_{\text{on } 1}^0$	1.3 $\mu\text{M}^{-1} \text{s}^{-1}$	[S9]
$k_{\text{on } 2}^0$	0.013 $\mu\text{M}^{-1} \text{s}^{-1}$	Estimated from sensitivity analysis, [S2]
$k_{\text{off } 1}^0$	0.47 $\text{s}^{-1}$ , 9.1 $\text{s}^{-1}$ (FLNB), 22 $\text{s}^{-1}$ (FLNA), or 41 $\text{s}^{-1}$	Calculated from $K_D$ Calculated from $K_D$ Calculated from $K_D$ Calculated from $K_D$
$k_{\text{off } 2}^0$	0.047 $\text{s}^{-1}$ , 0.91 $\text{s}^{-1}$ (FLNB),  2.21 $\text{s}^{-1}$ (FLNA), or 4.1 $\text{s}^{-1}$	Estimated from sensitivity analysis <sup>1</sup> , [S2]  Estimated from sensitivity analysis <sup>1</sup> , [S2]
$\Delta x^\alpha$	0.194 nm	[S3]
$\Delta x^\beta$	-0.194 nm	[S3]
$\chi$	8	[S2], sensitivity analysis <sup>1</sup>

<sup>1</sup>Extensive sensitivity analysis was performed based on parameters described in [S2] with little difference in the result with values above or below.

## Supplemental Materials and Procedures

### Cell culture

Jurkat cells were cultured in RPMI 1640 (Sigma-Aldrich) with 10% FBS (Life Technology). HeLa, Cos-7, and NIH 3T3 cells were cultured in DMEM (Life Technology) with 10% FBS. For MPA experiments, adherent cells were cultured on tissue-culture treated dishes (Corning), detached using 0.5% trypsin (Life Technology), centrifuged and resuspended in media. Cortical tension was calculated as described previously [S10]. Transient transfections were performed using FuGene HD (Promega) for adherent cells, and electroporation for Jurkat cells. For FRAP studies, HeLa cells were cultured on glass-bottom dishes (Corning) and transferred to Leibowitz Media (Life Technology) + 10% FBS four hours prior to imaging.

### Constructs

The following plasmids were acquired from Addgene:

Construct	Addgene Number	Resource
EGFP-C1- $\beta$ -actin	31949	Vladislav Verkhush [S11]
Mcherry-UtrCH-pCS2	26740	William Bement [S12]
mCherry-Ezrin-C14	55042	Michael Davidson
EGFP-C1-Talin	26724	Anna Huttenlocher [S13]
EGFP-N1-ACTN1	11908	Carol Otey [S14]
Mcherry-N1-coronin1B	27694	Christien Merrifield [S15]
E-cadherin-GFP	28009	Jennifer Stow [S16]
EGFP-C1-PH-PLC $\delta$	21179	Tobias Meyer [S17]
mCherry-C1-cofilin	27687	Christien Merrifield [S15]
EGFP-MLCK-C2	46316	Anne Bresnick [S18]

The Ras-binding domain sequence from human Raf and the PH domain of human AKT were cloned into the FUW2 vector, tagged with GFP and mCherry respectively. GFP tagged constructs for EGFP-C3-myosin IIA [S19], EGFP-C3-myosin IIB [S19], and EGFP-N3-myosin IIC [S20], were gifts from Robert Adelstein. CFP-C1-Kras, EYFP-C1-Rac1, mCherry-iBAR, and Lifeact-RFP-N1 were gifts from Allison Suarez and Takanari Inoue. EGFP-N1-ACTN4 was a gift from Allan Wells [S21]. A point mutation K255E was made in EGFP-N1-ACTN4 by site-directed mutagenesis to generate EGFP-N1-ACTN4 (K255E). The filamin A construct, pmdsRed-FLNA, was a gift from Fumihiko Nakamura. Filamin B full length construct EGFP-FLNB-pCI-C1, and hinge 1 deletion mutant construct EGFP-FLNB( $\Delta$ H1)-pCI-C1 were gifts from Arnoud Sonnenberg [S22]. Constructs for Septin 1 and 7, EGFP-N1-sept1 and EGFP-C1-sept7, were gifts from William Trimble [S23]. EYFP-paxillin and EGFP-vinculin were gifts from Susan Craig [S24]. GFP-anillin was stably expressed from a BAC and was a gift from Anthony Hyman [S25].

### Drug treatment

Myosin II light chain inhibitor ML7 (Sigma I2764) was dissolved in DMSO. The final concentration of DMSO in culture medium was kept below 0.15% during drug treatment. After resuspension, cells were treated with DMSO or ML7 for 15 minutes prior to imaging. ROCK inhibitor Y-27632 was dissolved in water, and cells were treated 30 minutes prior to imaging. For making measurements in mitotically arrested cells, 20  $\mu$ M STLC was added for 4 hours. Anaphase onset was induced by adding 30  $\mu$ M purvalanol A, followed by 15-30 minutes incubation. Microtubule depolymerisation was carried out by treating with 1  $\mu$ g/mL nocodazole for 4 hours.

### Measurements of mechanosensory response of proteins using micropipette aspiration

Micropipette aspiration was performed as described previously [S10]. In short, a pressure difference was generated by adjusting the height of a motor-driven water manometer. Mammalian cells expressing desired fluorescent proteins were loaded into the observation chamber, which was filled with either DMEM or RPMI 1640 medium depending on the cell type. Cell types were deformed equally using the ratio of the aspirated length of the cell in the pipette ( $L_p$ ) over the radius of the pipette ( $R_p$ ) as a guide. Once a pressure was determined for each cell type for which  $L_p/R_p$  was approximately equal to two, this fixed pressure was used for all cells of that type. These values were different between cell types (0.075 nN/ $\mu\text{m}^2$  for Jurkat cells, 0.15 nN/ $\mu\text{m}^2$  for NIH 3T3 cells, 0.2 nN/ $\mu\text{m}^2$  for HeLa cells, and 0.15 nN/ $\mu\text{m}^2$  for Cos-7 cells) due to the unique cortical tensions of these cells (**Fig. S2B**). Pressures higher than this often led to blebbing, or the separation of cell membrane from the cortex. All cells which demonstrated blebbing at any time during recording were discarded. Images were collected with an Olympus IX81 microscope equipped with MetaMorph software and analyzed using ImageJ (National Institutes of Health). After background correction, the fluorescence intensity at the accumulation sites inside the micropipette were normalized against the opposite cortex of the cell. This was repeated for each frame to obtain time-courses and account for expression level variation and photobleaching.

### Measurement of fluorescence recovery after photobleaching (FRAP)

FRAP was performed as described previously [S26]. HeLa cells were plated at low density on glass-bottom dishes and transiently transfected 40 hours prior to imaging. The culture media was changed to Leibowitz Media four hours prior to imaging. FRAP experiments were performed using a Zeiss AxioObserver with 780-Quasar confocal module, with a 63x (NA 1.4) objective at 37C and 5% CO<sub>2</sub>. A small region of the cell cortex was bleached using a 488 nm Argon laser, and the fluorescence recovery was recorded until recovery saturated (100 frames, 5-15 s/frame depending on the protein). The size and placement of the bleach region was kept relatively constant across measurements. For each frame, the average intensity of the bleached cortical region, reference (unbleached) region, and background was quantified using ImageJ (National Institutes of Health). For photobleaching correction, the reference theoretical intensity (RTI) was calculated by fitting the background subtracted reference intensity to an exponential decay equation as follows:

$$(1) \quad RTI(t) = A - B \cdot e^{-Ct}$$

where  $A$ ,  $B$  and  $C$  are fitting parameters.

The intensity of the bleached region was background subtracted and normalized to RTI. The normalized intensity (NI) was obtained by normalizing this to the pre-bleach intensity (average of 4 pre-bleach images), and was fitted to a single exponential as follows:

$$(2) \quad NI(t) = m_1(1 - m_2 \cdot e^{-kt})$$

Where  $m_1$ ,  $m_2$  are fitting parameters and  $k$  is the recovery rate.

The recovery time,  $\tau$ , and the immobile fraction,  $F_i$  were measured as:

$$(3) \quad \text{Recovery time, } \tau = 1/k$$

$$(4) \quad \text{Immobile fraction, } F_i = \frac{1-m_1}{1-m_1+m_2}$$

### Measurement of diffusion time by fluorescence correlation spectroscopy (FCS)

Jurkat (ACTN4) or HeLa (FLNB) cells were plated at low confluence in glass bottom dishes, transiently transfected 40 hours prior to imaging, and media was replaced with Leibowitz media 4 hours prior to imaging. FCS was performed exactly as previously described [S26] at 37C and 5% CO<sub>2</sub> on a Zeiss AxioObserver with 780-Quasar confocal module & FCS, with a C-Apochromat 40x (NA 1.2) water objective.

### Modeling the catch-bond behavior of $\alpha$ -actinin and filamin

A full explanation of the molecular model used to predict the behavior of  $\alpha$ -actinin and filamin in *Dictyostelium* is published [S2]. In short,  $\alpha$ -actinin is a dimer containing two actin-binding domains (ABD). One ABD of the protein first binds a single actin filament, where its diffusivity becomes greatly reduced, and it searches for a second filament to bind within a 3D sphere with a radius equal to the length of the protein rod. This binding reaction can be written as  $[Cr] + [F_1] \leftrightarrow [CrF_1] + [F_2] \leftrightarrow [CrF_1F_2]$  where  $Cr$ ,  $F_1$ , and  $F_2$  correspond to the crosslinker, the actin filament in the first step, and the actin filament in the second step, respectively. The reaction-diffusion equations used to model these conditions are as follows:

$$\begin{aligned}
 \frac{\partial [Cr]}{\partial t} &= D_1 \nabla^2 [Cr] - (k_{on1} [Cr][F_1] - k_{off1} [CrF_1]) \\
 (5) \quad \frac{\partial [CrF_1]}{\partial t} &= D_2 \nabla^2 [CrF_1] + (k_{on1} [Cr][F_1] - k_{off1} [CrF_1]) - (k_{on2} [CrF_1][F_2] - k_{off2} [CrF_1F_2]) \\
 \frac{\partial [CrF_1F_2]}{\partial t} &= D_3 \nabla^2 [CrF_1F_2] + (k_{on2} [CrF_1][F_2] - k_{off2} [CrF_1F_2])
 \end{aligned}$$

where  $D_1$ ,  $D_2$ , and  $D_3$  are the diffusion constants of  $Cr$ ,  $CrF_1$ , and  $CrF_1F_2$ , and  $k_{on1}$ ,  $k_{on2}$ ,  $k_{off1}$ , and  $k_{off2}$  are the on and off rates for the first and second steps, respectively. To simulate catch-bond behavior, we assumed the force-dependent binding condition would be the one in which the crosslinker is bound to two filaments. We used the following equation to make the second off rate slow with the application of force:

$$(6) \quad k_{off2} = k_{off2}^0 \exp(-f\Delta x/k_B T)$$

where  $k_{off2}^0$  is the zero-force off rate,  $f$  is the force applied, and  $\Delta x$  is the phenomenological bond length in a Bell-type model [S27].

Filamin also forms dimers and undergoes a two-step binding reaction with actin, however it binds orthogonal filaments which may not be at right angles, and different filament angles lead to different off rates for filamin [S3]. Thus, we use  $\alpha$  to denote angles less than 90°, and  $\beta$  to denote angles greater than 90° in the following reaction-diffusion equations for filamin:

$$\begin{aligned}
 \frac{\partial [Cr]}{\partial t} &= D_1 \nabla^2 [Cr] - (k_{on1} [Cr][F_1] - k_{off1} [CrF_1]) \\
 (7) \quad \frac{\partial [CrF_1]}{\partial t} &= D_2 \nabla^2 [CrF_1] + (k_{on1} [Cr][F_1] - k_{off1} [CrF_1]) - (k_{on2} [CrF_1] - k_{off2}^\alpha [Cr^\alpha F_1 F_2]) \\
 &\quad - (k_{on2} [CrF_1][F_2] - k_{off2}^\beta [Cr^\beta F_1 F_2]) \\
 \frac{\partial [Cr^\alpha F_1 F_2]}{\partial t} &= D_3 \nabla^2 [Cr^\alpha F_1 F_2] + (k_{on2} [CrF_1][F_2] - k_{off2}^\alpha [Cr^\alpha F_1 F_2])
 \end{aligned}$$



$$\frac{\partial [Cr^\beta F_1 F_2]}{\partial t} = D_3 \nabla^2 [Cr^\beta F_1 F_2] + \left( k_{\text{on}2} [Cr F_1] [F_2] - k_{\text{off}2}^\beta [Cr^\beta F_1 F_2] \right)$$

In the case of filamin, we used **Equation 6** to incorporate catch-bond behavior into  $k_{\text{off}2}$ , but also incorporated structural cooperativity into  $k_{\text{on}2}$  using the following equation:

$$(8) \quad k_{\text{on}2} = k_{\text{on}2}^0 \left( 1 + \frac{[Cr^\alpha F_1 F_2] + [Cr^\beta F_1 F_2]}{F_2} \right)^{x \cos \theta}$$

where  $x$  is the cooperativity index and  $\theta$  is the azimuth angle in the tip of an aspirated cell. See **Table S1** and **Table S2** for the parameters used for each variable.

### Statistical analysis

Statistical analysis was performed using Graph Prism ([www.graphpad.com](http://www.graphpad.com)) or KaleidaGraph (Synergy Software). The Mann-Whitney test was used for non-parametric comparisons of different data sets. Data sets were also analyzed by analysis of variance (ANOVA) with a Fisher's least significant difference comparison. Both methods obtained nearly identical conclusions.

## Supplemental References

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