

Intrinsically disordered region of talin's FERM domain functions as an initial PIP₂ recognition site

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2021-09-07

Focal adhesions mediate the interaction of the cytoskeleton with the extracellular matrix (ECM). Cell-ECM adhesion is used by almost all cells both during development and homeostasis and ranges from dynamic to permanent. As such, it is an important process in health and disease alike. Talin is a central regulator and adaptorprotein of the multiprotein focal adhesion complexes and is responsible for integrin activation and force-sensing. We evaluated direct interactions of talin with the membrane lipid phosphatidylinositol 4,5-bisphosphate (PIP₂) by means of molecular dynamics simulations. A newly published autoinhibitory structure of talin, where common PIP₂ interaction sites are covered up, sparked our curiosity for a hitherto less examined loop as a potential site of first contact. We show that this unstructured loop in the F1 subdomain of the talin1 FERM domain is able to interact with PIP₂ and can facilitate further interactions by serving as a flexible membrane anchor. This work presents the dynamics of the interaction and identifies key residues. Further, we surveyed the effect of a physiological PIP₂ enrichment at focal adhesion sites on the dynamics of talin through force-probe molecular dynamics simulations. The results provide backing for the direct involvement of PIP₂ in the localization and activation of talin.

⚠ Warning

This is a draft and as such subject to change.

💡 Tip

You can find the poster that goes along with the paper presented at the [Annual Meeting of the Biophysical Society 2022](#) in your favorite format here: [web/html](#), [print/pdf](#) The source repository for this paper lives [here](#)

Introduction

It is critical for cells to mechanically sense their surroundings at cell adhesion sites for a multitude of biological processes. Contact with the extracellular matrix and surrounding cells regulates growth, differentiation, motility and even apoptosis (1–4). The multiprotein focal adhesion complex is responsible for translating between biochemical and mechanical signals, where both directions, outside-in and inside-out activation, are being investigated (5, 6).

At the center of the focal adhesion complex sits the adaptorprotein talin, which dynamically unfolds and refolds under force (7). A schematic of Talin can be seen in Figure 1a. Through interaction with integrin tails (dark green), which in turn interact with collagen fibers via their heads, it links the extracellular matrix to the intracellular cytoskeleton by directly interacting with actin and increasing integrins affinity for ligands, thereby activating it (8).

Talin features an N-terminal FERM domain (F for 4.1 protein, E for ezrin, R for radixin and M for moesin) which provides the link to the cytosolic side of the plasma membrane (9). It does so via a conserved binding motif for phosphatidylinositol 4,5-bisphosphate (PIP_2), which is enriched at active focal adhesion sites (10–12). In the figures we color the individual subdomains F0-F3. The main binding sites in F2 and F3 are highlighted with red spheres. Notably, the Talin1 FERM domain differs from other FERM proteins through the addition of the F0 subdomain, which is connected to F1 via a charged interface, as well as an insert in F1, a flexible loop with helical propensity and basic residues (13). Additionally, it exists in an extended conformation, as opposed to the cloverleaf-like conformation of other FERM proteins (14). F3 also has a binding site for β -integrin tails (15) and is partly responsible for the enrichment of PIP_2 at the membrane through a binding site for $\text{PIP}\text{K}\gamma$ (16). A second integrin binding site is located with the rod domains 11 (R11) (17). On the other hand talin interacts with the cytoskeleton through actin binding sites (F2-F3, R4-R8, R13-DH) (18). The review by Klapholz et al. (19) provides an excellent overview of the many interaction sites of talin and its central role in the focal adhesion complex.

It was previously shown that F3 can interact with R9, which hinders integrin activation (20) and recently Dedden et al. (21) published a novel cryo-Electron Microscopy structure of the autoinhibited Talin1. They showed that the rod domains R9 and R12 shield the established PIP_2 binding surface and the integrin binding site in F3. This beckons the question how this autoinhibition can be resolved. Song et al. (12) had previously investigated a fragment of talin consisting of F2-F3 and an inhibiting rod segment and suggested a pull-push mechanism, whereby negatively charged PIP_2 attracts its positively charged binding surface on F2-F3 and simultaneously repels the negatively charged surface of the inhibitive rod segment. However, this still leaves open the question of how talin can establish a first contact with the membrane and remain within a sufficient proximity for this effect to kick in.

In order to investigate this we looked at the additional flexible F1 loop, which had been shown to be important for talin mediated integrin activation (13), but was only considered a minor PIP_2 binding site compared to the main site in F2-F3 (22, 23).

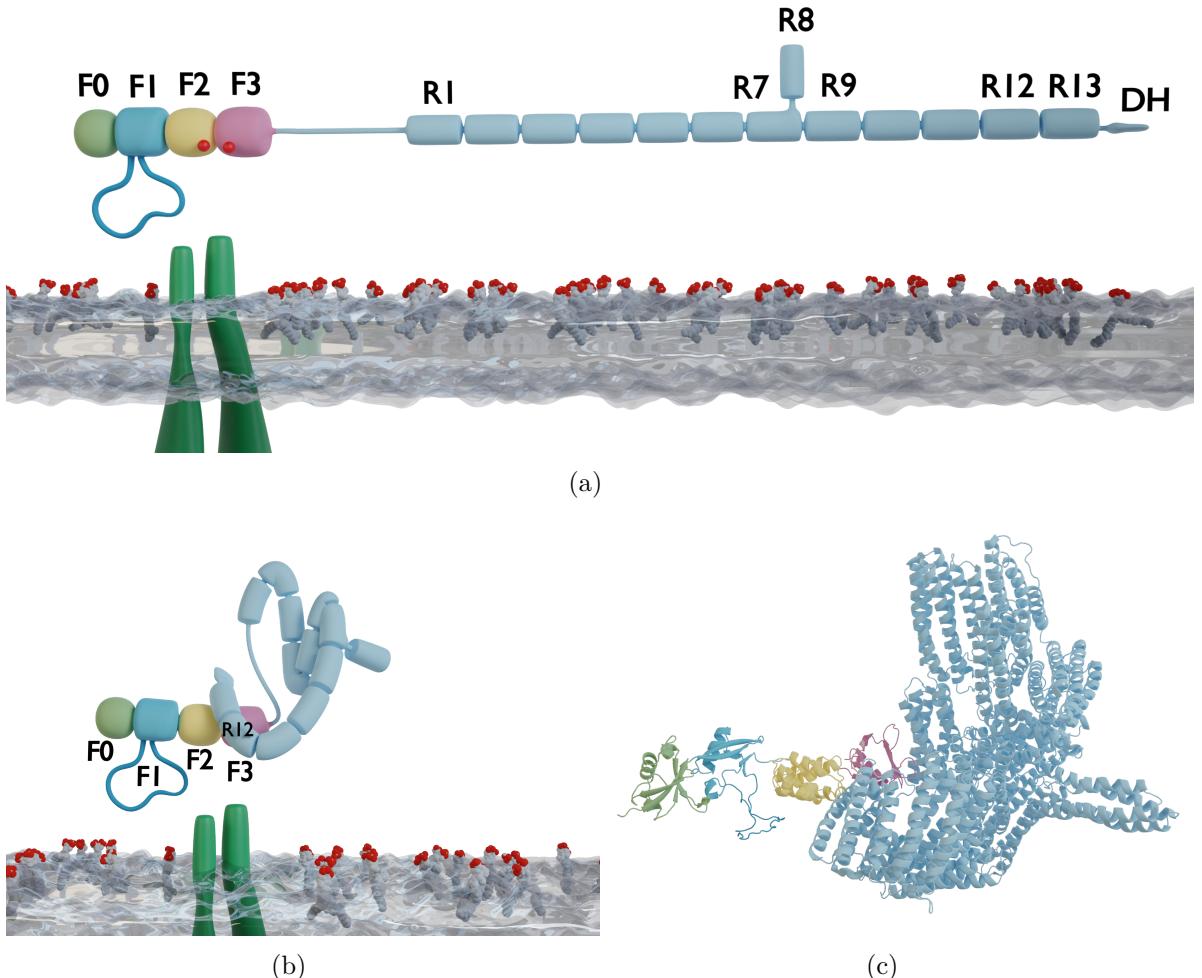


Figure 1: A schematic overview of Talin and our simulation setup. **a)** A schematic rendering of full-length Talin over a POPC membrane enriched with PIP₂ in the upper leaflet. The subdomains under scrutiny in this publication, namely F0-F3, which comprise the N-terminal FERM domain (or talin head) are highlighted in pastel colors (green, cyan, yellow, magenta). The two major PIP₂ binding sites in F2-F3 are marked with red spheres. An integrin binding site also resides in this area. Klapholz et al. (19) provide an excellent review of Talin's central role in the focal adhesion complex and list further binding sites. The talin rod segments (or talin tail) are numbered R1 to R13. Note, that under physiological conditions with talin experiencing force from bound actin the angle between the FERM domain and the talin rod would be more akin to 30° as opposed to the linear structure used here for illustrative purposes. Tails of an integrin α and β heterodimer reaching through the lipid bilayer are represented in green. **b)** A schematic rendering of the autoinhibited structure of Talin as crystallized by Dedden et al. (21) in combination with a cartoon representation in **c)**. The completed FERM structure by Elliott et al. (14), with our addition of the modelled F1 loop, is fitted to the autoinhibited structure, as the latter does not include F0-F1 due to their flexibility. The main PIP₂-binding sites in F2-F3 are occluded by rod domain 12. Additionally, R9 covers up the integrin binding site.

Due to its high flexibility, the loop itself is not included in crystal structures of the FERM domain, such as PDB-ID 3IVF by Elliot et al. (14). Its high flexibility however also gave use the confidence to model it from sequence. The retained flexibility in equilibrium simulations (Figure 5a) as well as comparisons to NMR structures (13) confirmed this approach.

With a complete structure of the talin FERM domain we investigated the role of the F1 loop through molecular dynamics simulations. By taking a closer look at just F0-F1, we first show that the loop has a clear propensity to interact with the PIP₂-containing membrane and is able to establish a first contact with it even from unfavorable initial conformations due to its large search volume. Furthermore, we show with simulations of the full-length FERM domain that once the loop has established an initial contact, it can anchor the FERM domain to the membrane and re-establish the known major binding sites in F2-F3.

Materials and Methods

Molecular dynamics with GROMACS

Molecular dynamics simulations were performed with GROMACS (24, 25) version 2020.03 (26). A crystal structure of the Talin FERM domain by Elliot et al. (14) with the PDB-ID 3IVF was used as the basis of all simulations.

3IVF

The missing F1 domain loop between residues L133 and W144 was modeled using MODELLER (27, 28) via the interface to Chimera (29), followed by equilibration with GROMACS. The resulting conformation was compared to an NMR structure of the F1 domain (PDB-ID 2KC2) by Goult et al. (13).

The missing residue M1 was also added. The missing residues I399 and L400 were not modeled, leaving us with a continuous sequence from residue 1 to 398. Simulations were performed with the CHARMM36 force field. Topologies, including the membrane, were generated with the CHARMM-GUI web app (30–32) and GROMACS tools. All simulations used the TIP3P water model and were neutralized with 0.15 mol/L of NaCl. A 6-step equilibration was performed after gradient decent energy minimization while gradually relieving restraints on protein and membrane atoms. Production runs use a timestep of 2 fs, a Verlet cut-off scheme for Van-der-Waals interactions and the Particle Mesh Ewald (PME) method for long-range electrostatics. NTP-ensembles were achieved by Nosé-Hoover temperature coupling (33, 34) and Parrinello-Rahman pressure coupling (35). An example .mdp-file can be found in the supplementary materials at Section .

The initial equilibrium simulation of the completed FERM domain was run for 75 ns. Subsequently, the root mean squared fluctuation (RMSF) was calculated with GROMACS tools.

The F0F1 FERM sub domains (residues 1 to 197) were simulated to evaluate protein-membrane association using a rotational sampling approach. This entailed placing the protein 1.5 nm away from a 1-palmitoyl-2-oleoyl-glycero-3-phosphocholine (POPC) membrane in a total of 60 orientations spanning a rotation of 360 degrees. 6 replicates of each orientation were run for 200 ns each. However, due to a hardware failure, 6 of these 360 runs are only 50 to 150 ns long. Of the 119 lipids in the upper leaflet of the POPC membrane, 12 lipids were replaced with PIP₂, which results in a physiological concentration of 10% PIP₂.

From this rotational sampling, we selected representative conformations with high protein-membrane interaction as the basis of 6 equilibrium simulations of the complete FERM domain over a POPC membrane with 26 PIP₂ lipids out of a total of 273 lipids in the upper leaflet. Each simulation ran for 400 ns. The initial conformations for perpendicular pulling simulations of the F0F1 subdomains to gauge interaction strength were also chose from the rotational sampling set.

To compare the effects of PIP₂ on the dynamics, a system containing only 1 % PIP₂ (3 PIP₂ molecules in 273 lipids) was created from the enriched system by programmatically exchanging lipid head groups via a python script. The enriched and non-enriched systems were then subjected to force-probe MD simulations.

Automation, Data Analysis and Availability

Setup scripts written in bash are available for all simulations shown in this work. Plots were generated with R using ggplot2 (36). Interactive structure representations are embedded using Mol* (37). Schematic visualizations were rendered with blender (38) and VMD (39). Files relevant to this paper that are too big to be uploaded to this repository, such as trajectories and blender files, will be uploaded to a separate location.

This paper and the matching poster were generated with [quarto](#) (40) and Rmarkdown (41, 42).

Results

The F1 loop can act as a point of first contact

When simulating F0-F1 over a POPC membrane containing 10% PIP₂ we noticed that the F1 loop had a clear propensity to establish contact with the membrane. And once contact had been established the protein was anchored strongly enough for more contacts to evolve with time, pulling the protein onto the membrane (see Figure 2a, 2b, 2c). In order to control for a potential bias towards the loop as a result of the starting position we performed a rotational sampling of the system, where the starting angle of the loop with respect to the membrane was varied across 60 equally spaced angles. Figure 2d shows that independent of the starting

position, the loop is able to find the membrane and bind to it, though this does happen earlier in the simulation when the loop starts favorably oriented towards the membrane (Figure 2e). However, even in its most unfavorable starting orientation (180°, oriented away from the membrane) the loop is able to find the membrane due to the large search space it can cover with its high flexibility (see Figure 5a).

Once contact has been made, it becomes exceedingly unlikely for F0-F1 to dissociate from the membrane (Figure 2f). Of 358 runs¹, 89 runs never made contact with the membrane, but out of the 269 that did, only 10 eventually dissociated. Figure 2g and ?@fig-f0f1-residues highlight the residues involved in the interaction.

The F1 loop can facilitate further contacts

We chose a representative conformation from the rotational sampling as a starting point for force-probe simulations of F0-F1 perpendicular to the membrane (Figure 3a) to test the strength of the interaction. An exemplary render of one of the simulations can be seen in ?@fig-f0f1-pull-run-1. Pulling F0-F1 off the membrane requires peak forces of 100–120 pN, during which the interacting residues only very gradually loose contact (Figure 3b). This highlights the strong anchoring capabilities of the loop. Its high flexibility allows it to remain in contact with the membrane over large distances, which would allow for a spring-like re-establishing of more contacts should the force be alleviated.

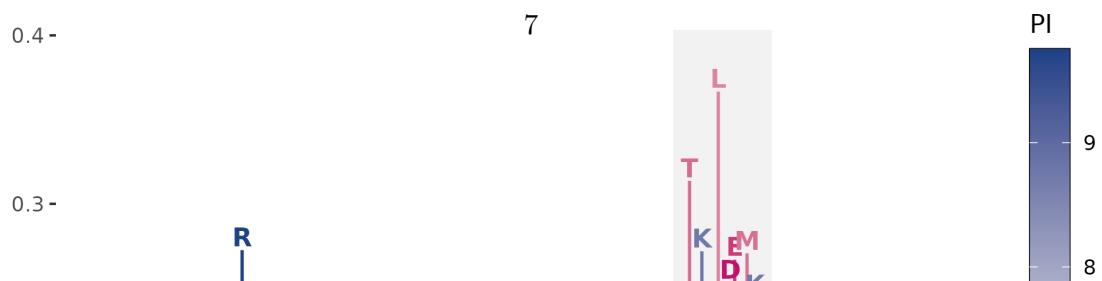
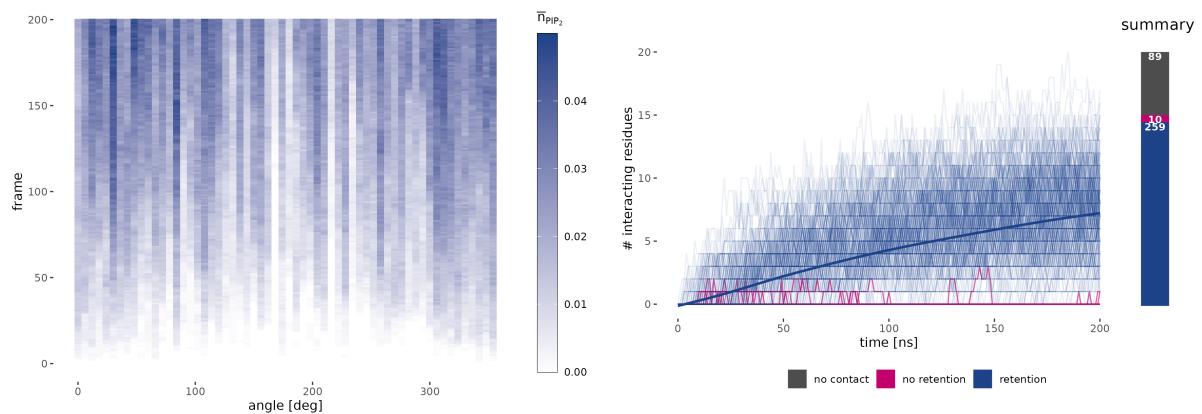
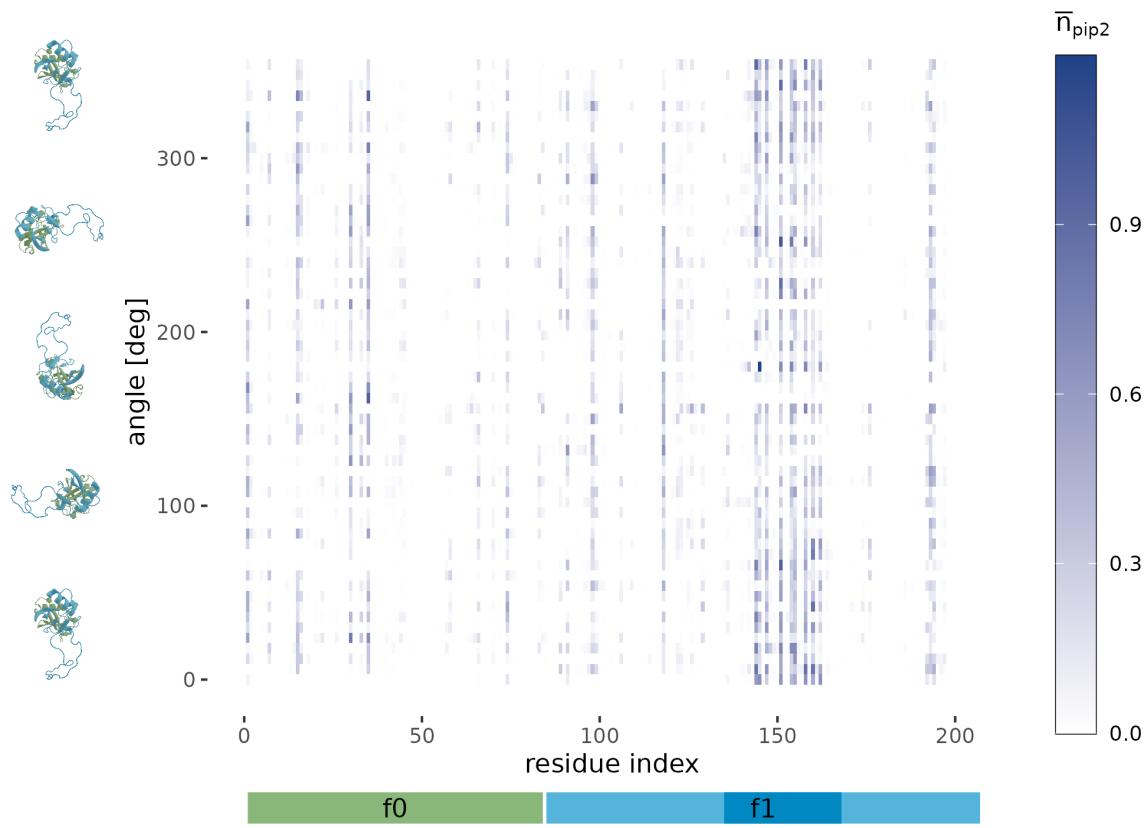
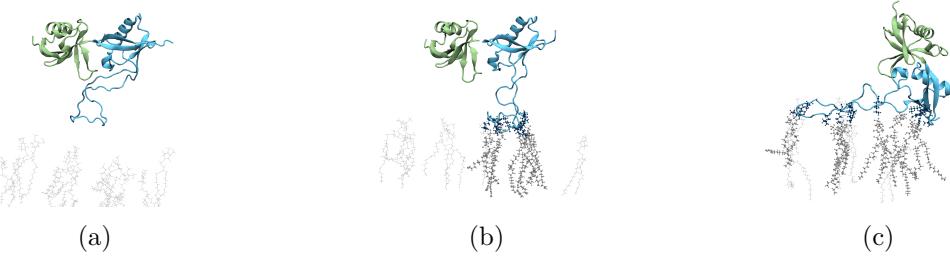
Simulations with the full-length FERM domain show that with the loop as an initial membrane contact, known PIP₂ binding sites can also be established as well (Figure 4a, Figure 4b). The highlighted residues include K272 of F2 and K316, K324, E342, and K343 of F3, which have been shown to be crucial for the membrane interaction of Talin and subsequent integrin activation by Chinthalapudi et al. (22).

The FERM domain adds lateral friction to aid in localizing Talin at the membrane

Note

Additional simulations pulling the whole FERM domain at a physiological angle of 30° laterally over a membrane with differing concentrations of PIP₂ are currently running.

¹6 replicas each for 60 angles minus 2 runs lost to a storage failure



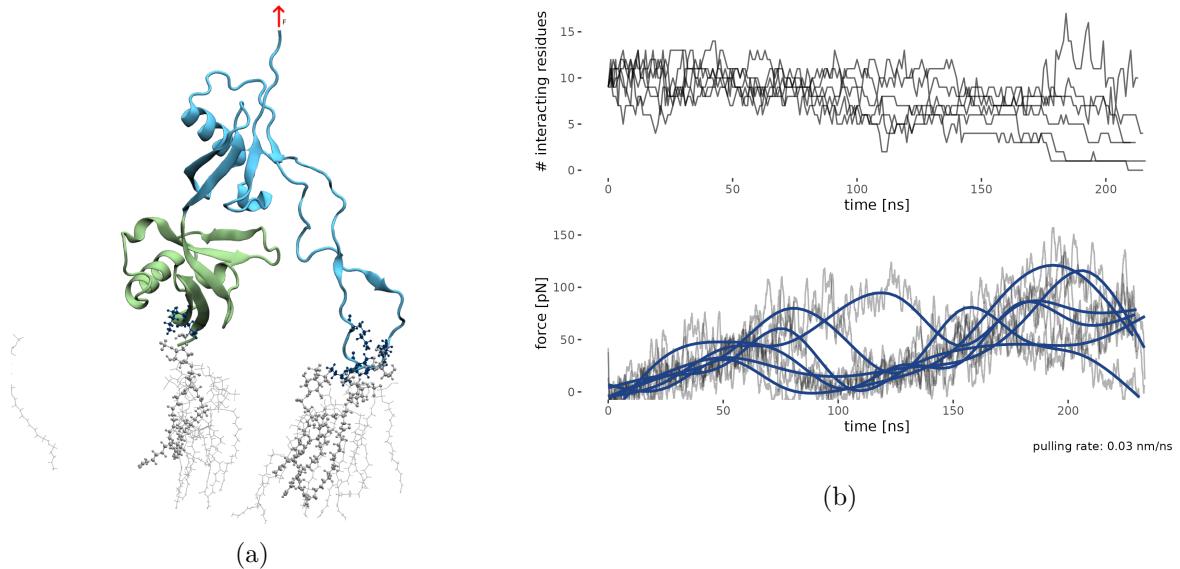
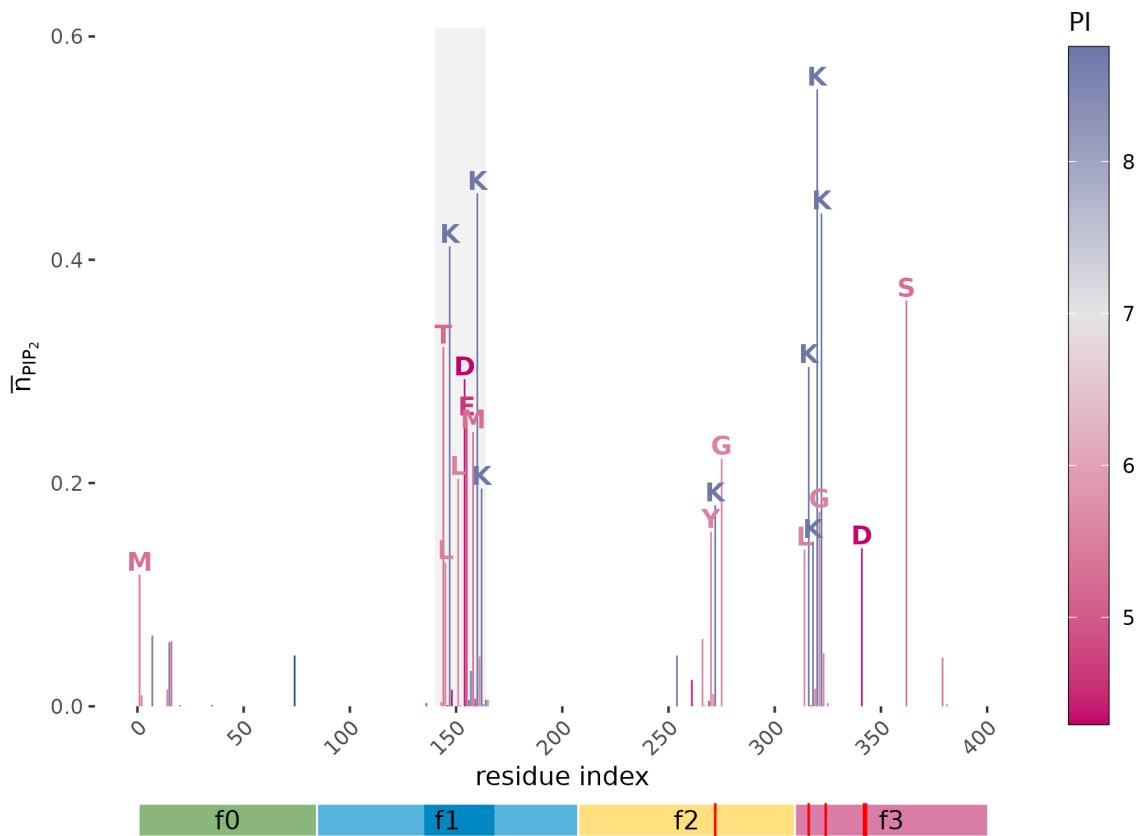
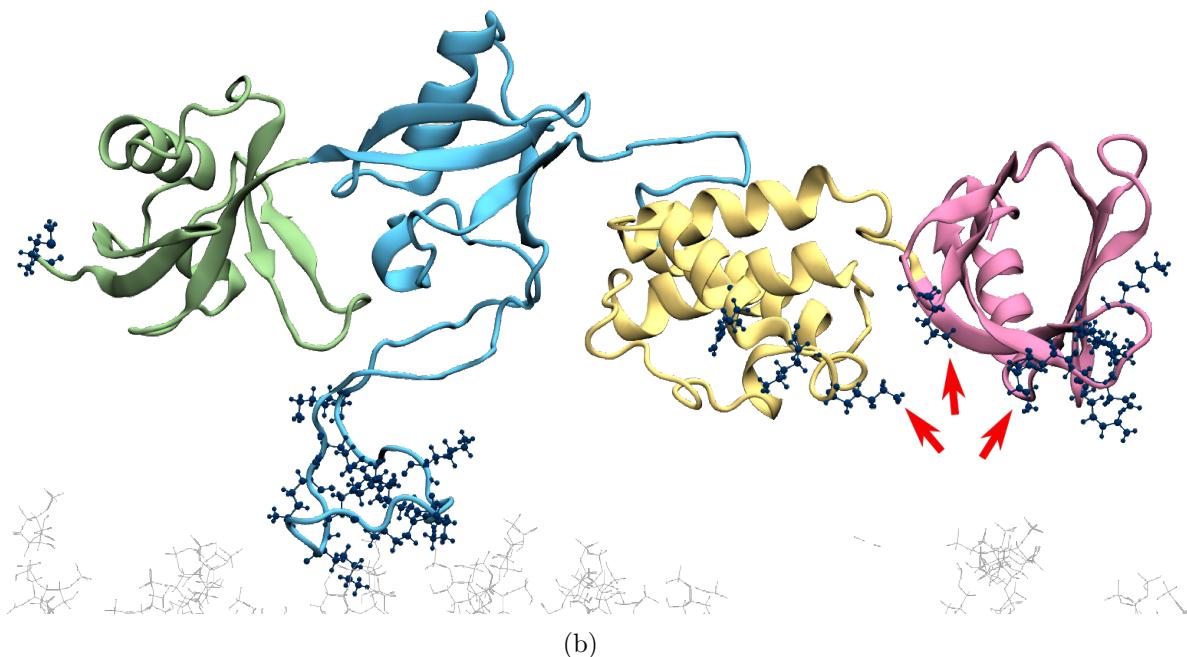


Figure 3: Vertical Pulling of F0-F1. **a)** A representative render of one of 6 force-probe MD simulations pulling F0-F1 off the membrane. It starts from a snapshot of F0-F1 in its bound conformation taken from the rotational sampling (Figure 2) and gets pulled upwards from its C-terminus. The direction of force is shown in the snapshot **b)**. **c)** As F0-F1 gets pulled at a constant rate of 0.03 nm/ns we observe the time evolution of the force (bottom panel) and the number of interacting residues (top panel). The number of interacting residues goes down very gradually, as the high flexibility of loop allows the residues to remain in contact even as the distance increases.



(a)



(b)

Figure 4: Simulation of the full-length FERM domain over a 10% PIP_2 -membrane. **a)** The Mean interaction scores of the individual residues across 6 simulations. Color represents the isoelectric point of the amino acid in isolation (blue = basic, magenta = acidic). The known PIP_2 interaction sites K272 of F2 and K316, K324, E342, and K343 of F3 (22) are highlighted with red lines on the x-axis colorbar and can also be seen in the cartoon representation in **b)** where the main interacting residues are displayed as dark blue stick models.

Discussion and Outlook

Author Contributions

Conceived and designed the experiments: JB FF FG. Performed the experiments: JB FF. Analyzed the data: JB FF. Contributed reagents/materials/analysis tools: FF. Wrote the paper: JB.

Acknowledgments

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 101002812).

Supplementary Material

Scripts

Note

Analysis scripts, setup scripts and production trajectories will be uploaded and linked here.

Production run parameters

```
integrator      = md
dt              = 0.002
nsteps          = 100000000
nstxout         = 5000
nstvout         = 5000
nstfout         = 50000
nstcalcenergy   = 100
nstenergy        = 1000
nstlog          = 1000
cutoff-scheme   = Verlet
```

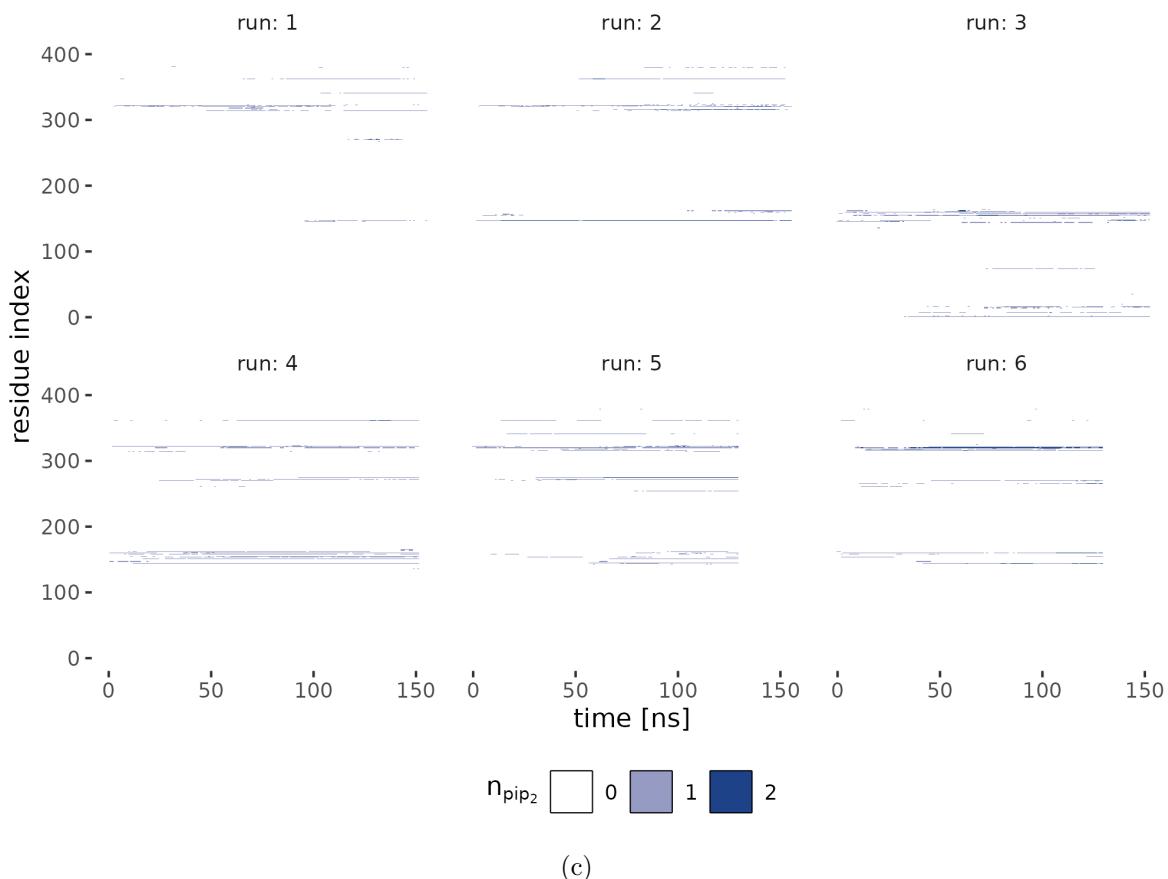
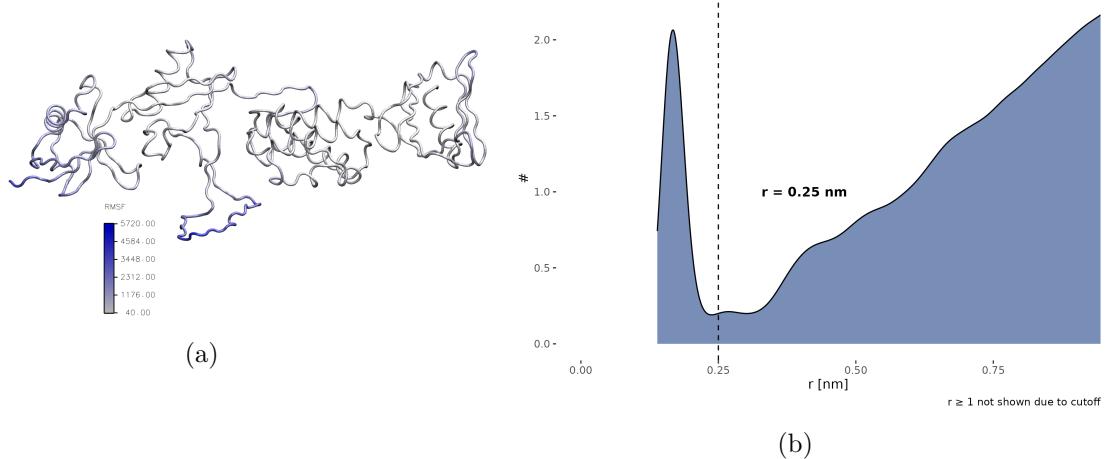


Table 1: Talin1 FERM domain boundaries

Domain	From	To
F0	1	84
F1	85	207
F2	208	309
F3	310	400

Table 2: Top residues interacting with F0F1

Residue	Mean #PIP ₂
M 1	0.188
K 15	0.184
R 30	0.173
R 35	0.245
R 74	0.124
K 98	0.176
R 118	0.209
T 144	0.299
L 145	0.168
K 147	0.263

Table 3: Top residues interacting with FERM

Residue	Mean #PIP ₂
M 1	0.118
T 144	0.322
L 145	0.129
K 147	0.412
L 151	0.204
D 154	0.293
E 155	0.257
M 158	0.246
K 160	0.459
K 162	0.195

```

nstlist          = 20
rlist           = 1.2
coulombtype    = pme
rcoulomb       = 1.2
vdwtype        = Cut-off
vdw-modifier   = Force-switch
rvdw_switch    = 1.0
rvdw           = 1.2
tcoupl          = Nose-Hoover
tc_grps         = SYSTEM
tau_t           = 1.0
ref_t           = 303.15
pcoupl          = Parrinello-Rahman
pcoupltype     = semiisotropic
tau_p           = 5.0
compressibility = 4.5e-5 4.5e-5
ref_p           = 1.0    1.0
constraints     = h-bonds
constraint_algorithm = LINCS
continuation    = yes
nstcomm         = 100
comm_mode       = linear
comm_grps       = SYSTEM
refcoord_scaling = com

```

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