

Title

Titin-based force regulates cardiac myofilament structures mediating length-dependent activation

Authors

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Short title

Titin manipulates sarcomere structures

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1 Abstract

2 The Frank-Starling law states that the heart's stroke volume increases with greater preload due to
3 increased venous return, allowing the heart to adapt to varying circulatory demands. Molecularly,
4 increasing preload increases sarcomere length (SL), which alters sarcomere structures that are correlated
5 to increased calcium sensitivity upon activation. The titin protein, spanning the half-sarcomere, acts as a
6 spring in the I-band, applying a SL-dependent force suggested to pull against and alter myofilaments in a
7 way that supports the Frank-Starling effect. To evaluate this, we employed the titin cleavage (TC) model,
8 where a tobacco-etch virus protease recognition site is inserted into distal I-band titin and allows for
9 rapid, specific cleavage of titin in an otherwise-healthy sarcomere. Here, we evaluated the atomic-level
10 structures of amyopathic cardiac myofilaments following 50% titin cleavage under passive stretch
11 conditions using small-angle X-ray diffraction, which measures these structures under near-physiological
12 (functional) conditions. We report that titin-based forces in permeabilized papillary muscle regulate both
13 thick and thin myofilament structures clearly supporting titin's role in the Frank-Starling mechanism.

14 Main Text

15 The famous Frank-Starling law states that the heart's stroke volume increases with greater preload due to
16 increased venous return, allowing the heart to adapt to varying circulatory demands. Molecularly,
17 increasing preload increases sarcomere length (SL), which alters sarcomere structures that are correlated
18 to increased calcium sensitivity upon activation. The titin protein, spanning the half-sarcomere (Fig. 1A),
19 acts as a spring in the I-band, applying a SL-dependent force suggested to pull against and alter
20 myofilaments, critically supporting the Frank-Starling effect.¹ Altered titin-based forces play a crucial role
21 in the etiology of many cardiomyopathies; however, the disease state obscures titin's role, impeding
22 therapeutic solutions. We solved this problem using the titin cleavage (TC) model, where a tobacco-etch
23 virus protease (TEV_P) recognition site is inserted into distal I-band titin and allows for rapid, specific
24 cleavage of titin in an otherwise-healthy sarcomere.² Titin cleavage decreases myocardial passive force
25 and stiffness while altering cardiomyocyte tensegrity.² Here, we evaluated the atomic-level structures of
26 amyopathic cardiac myofilaments following 50% titin cleavage under passive stretch conditions using
27 small-angle X-ray diffraction, which measures these structures under near-physiological (functional)
28 conditions.¹

29 We prepared permeabilized papillary muscle from genotypically heterozygote TC mice (left ventricles)
30 and placed them in a bath of physiological relaxing solution attached to a mechanics apparatus, as
31 reported.³ Diffraction patterns (Fig. 1B) were collected from each preparation at an initial length just
32 above slack (100% L₀; ~1.9 μm SL)² and at 110% L₀. The sample was then incubated with TEV_P (100
33 units acTEV in 300 ml relaxing solution) for 20 minutes, sufficient to cleave 50% titins,² rinsed, and the
34 protocol repeated. Diffraction patterns were analyzed using the freeware MuscleX.^{1,3} For each parameter,
35 we used a mixed-model ANOVA, with fixed effects length, treatment (pre/post), interaction, and a
36 repeated-measures random effect (individual). Model assumptions were assessed via residual analysis, the
37 significance level was P=0.05, and all data was reported as mean±s.e.m. For brevity, the main effect P-
38 values are within Fig. 1.

39 The lateral myofilament lattice spacing is influenced by titin-based forces and was evaluated via the 1,0
40 reflection, produced from the geometric planes within the thick-thin filament overlap.¹ Before and after
41 TEV_P treatment, the spacing of the 1,0 (d₁₀; Fig. 1C) reflection decreased with increasing SL, though the
42 lattice was expanded after titin cleavage, as was expected when some but not all titins are cleaved.³ We
43 quantified myofibrillar and myofilament orientation, a determinate of cardiomyopathies,¹ using the
44 angular spread of the 1,0 reflections (angle σ; Fig. 1D), and found greater disorientation after titin
45 cleavage, highlighting a role for titin-based force in papillary-wide order.⁴

46 Increasing titin-based forces at longer SLs could stretch the cardiac thick filament, accompanied by a
47 transition of some myosin heads from an OFF to an ON confirmation. This mechanism may increase the
48 myosin head's ability to form crossbridges, contributing to the Frank-Starling effect.¹ Here, we show that
49 the spacing of the M6 (S_{M6}; Fig. 1E), a measure of thick filament length, increases at the longer SL and
50 decreases with 50% titin cleavage. We further observed myosin head OFF-to-ON transition with
51 increasing SL before cleavage, as indicated by increasing M3 spacing (S_{M3}; Fig. 1F; axial periodicity of
52 crowns), decreasing √M3 intensity (√I_{M3}; Fig. 1G; proportional to number of ordered heads), and
53 increasing ratio between the intensities of 1,1 and 1,0 reflections (I₁₁/I₁₀; Fig. 1H; mass distribution
54 between thick and thin filaments). Importantly, 50% titin cleavage decreased S_{M3} and increased √I_{M3},
55 suggesting myosin head ON-to-OFF transitions; however, I₁₁/I₁₀ presented no change. Therefore, the
56 radial position of myosin heads (I₁₁/I₁₀) may not change, while myosin heads still reorient (S_{M3}; √I_{M3}). As
57 a cautionary note, I₁₁/I₁₀ can be affected by lattice changes, as caused by titin cleavage (Fig. 1C-D). We

58 conclude that reducing titin-based forces leads to a myosin head ON-to-OFF transition while leaving the
59 length-dependent OFF-to-ON transition mechanism intact.

60 Interestingly, thin filament length, as measured by the A6 reflection spacing (S_{A6} ; Fig. 1I), also increased
61 with increasing SL, and of note, decreased after titin cleavage, similar to TC skeletal muscle.³ The length
62 change of the thin filament is perplexing, as titin is not in an ideal position to stretch it. We postulate that
63 low-level crossbridges in passive cardiac muscle⁵ are recruited from the ON-state motors and transmit
64 strain to the thin filament; less ON-state heads leads to fewer crossbridges and thus shorter thin filaments.
65 This hypothesis is supported by a significant negative correlation between $\sqrt{I_{M3}}$ and S_{A6} (Fig. 1J). The
66 physiological meaning of this phenomenon remains to be elucidated.

67 In summary, titin-based forces in permeabilized papillary muscle regulate both thick and thin
68 myofilament structures (Fig. 1K), clearly supporting titin's role in the Frank-Starling mechanism. Further
69 details could be provided using intact TC cardiac preparations, but the experiment requires shuttling
70 TEV_P into intact preparations, which is a future goal. A study of TC papillary muscle during contraction is
71 the next logical step.

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104 **Figure Legend**

105 **Figure 1. Molecular changes to cardiac sarcomeres after 50% titin cleavage.** **A.** Schematic of a half-
106 sarcomere with myosin heads shown in ON (green) and off (gray) states. In the titin-cleavage model, I-
107 band titin is cleavable at the TEV protease recognition site (scissors). **B.** An X-ray diffraction pattern of
108 permeabilized TC papillary muscle, with markers of interest labeled. **C-I.** Analysis of myofilament
109 structures at different sarcomere lengths (expressed as length relative to slack (L_0)), before (gray) and
110 after (blue) 50% titin cleavage. Both the technical diffraction nomenclature, as well as what they
111 represent, are included. Overlaid are the main effects ANOVA results for length (L) and treatment (T).
112 Interaction main effects were never significant ($P > 0.05$). **J.** Regression analysis between $\sqrt{I_{M3}}$ intensity
113 ($\sqrt{I_{M3}}$) and A6 spacing (S_{A6}), with R^2 and P-value included. **K.** A summary of our findings for sarcomeric
114 structures at short (top) and long (bottom) lengths. We directly demonstrate a relationship between titin-
115 based forces and the myosin head OFF-to-ON transition. Datasets are generated from papillary muscle
116 preparations of 28 heterozygote TC hearts, age range 4-9 months, and presented as mean \pm s.e.m.

117 **Figure**

