21st International Conference on Composite Materials
Xi'an, 20-25th August 2017

A Tensegrity Model of Cells under Stretches

Guang-Kui Xu

International Center for Applied Mechanics, State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China

Email: guangkuixu@mail.xjtu.edu.cn
Web: http://gr.xjtu.edu.cn/web/guangkuixu

Keywords: Cell materials, Stretches, Tensegrity, Substrate Stiffness

ABSTRACT

Deciphering the mechanisms underlying the high sensitivity of cells to mechanical microenvironments is crucial for understanding many physiological and pathological processes, e.g. stem cell differentiation and cancer cell metastasis. Here, a cytoskeletal tensegrity model is proposed to study the reorientation of polarized cells on a substrate under biaxial cyclic deformation. The model consists of four bars, representing the longitudinal stress fibers and lateral actin network, and eight strings, denoting the microfilaments. It is found that the lateral bars in the tensegrity, which have been neglected in most of the existing models, can play a vital role in regulating the cellular orientation. The steady orientation of cells can be quantitatively determined by the geometric dimensions and elastic properties of the tensegrity elements, as well as the frequency and biaxial ratio of the cyclic stretches. It is shown that this tensegrity model can reproduce all available experimental observations. For example, the dynamics of cell reorientation is captured by an exponential scaling law with a characteristic time that is independent of the loading frequency at high frequencies and scales inversely with the square of the strain amplitude. This study suggests that tensegrity type models may be further developed to understand cellular responses to mechanical microenvironments and provide guidance for engineering delicate cellular mechanosensing systems.

1 INTRODUCTION

Various physiological processes, such as stem cell differentiation and heart beating, rely on the precise response of cells to their mechanical microenvironments [1,2]. Deciphering the mechanisms underlying high cellular sensitivity to the dynamic stimuli is fundamental for understanding these processes. Experiments have shown that the polarized cells align in parallel to the stretching direction when the underpinning substrate is subjected to a static tensile strain [3]. Under uniaxial cyclic stretch, cells align along the direction perpendicular to the loading direction at frequencies around 1 Hz [4]. A few theoretical models based on cytoskeletal stress and strain have been developed to explain the different orientations of cells in response to static and dynamic loadings [5]. In many physiological processes (e.g., heart beating, pulsating blood vessels and breathing), cells and their extracellular matrix are exposed to biaxial cyclic deformations. Recently, experiments showed that the steady cellular orientations under biaxial cyclic stretches are incompatible with the existing stress- or strain-based models, and can be explained by using a model based on the passively stored elastic energy in the cell [6]. To date, however, how cellular alignment is precisely regulated and what mechanistic principles govern the high cellular sensitivity remain elusive.

2 GENERAL SPECIFICATIONS

We propose for the first time a cytoskeletal tensegrity model to study the reorientation of polarized cells on a substrate under stretches [7]. The tensegrity is modeled by four bars, representing the longitudinal stress fibers and lateral microtubules, and eight strings, denoting the microfilaments. It is found that the lateral bars in the tensegrity, which have been neglected in most of the existing models, can play a vital role in regulating the cellular orientation. Under biaxial static strains, the cell will align in parallel to the stretching direction, in agreement with the experimental observations. The dynamic response of stress fibers in the tensegrity to the applied strains is limited by the actin binding/unbinding velocity and the intrinsic viscosity of molecular motors. Due to this mechanism, the mechanical response of cells is sensitive to the frequency of cyclic loads. Under biaxial cyclic strains, the steady orientation of cells can be quantitatively determined by the geometric dimensions and elastic properties of the tensegrity elements, as well as the frequency and biaxial ratio of the cyclic strains. It is demonstrated that the dynamic process of cell reorientation follows an exponential law with a characteristic time which scales inversely with the square of the stretch amplitude, decreases with the cycling frequency, and saturates beyond a threshold frequency. Moreover, we examined the relation between the elastic moduli of a single cell and cell groups, and showed that the elasticity of cell groups is remarkably enhanced because of the rotational confinement on the bars of tensegrity under stretches. We have shown that the predictions of our tensegrity model are in broad agreement with many different types of experimental phenomena. This study suggests that tensegrity type models may be further developed to understand the high cellular sensitivity and provide guidance for engineering delicate cellular mechanosensing systems.

ACKNOWLEDGEMENTS

Financial supports from the National Natural Science Foundation of China (Grant Nos. 11402193, and 11672227) and the Young Elite Scientist Sponsorship Program by CAST (No. 2015QNRC001) are acknowledged.

REFERENCES

[1] D. E. Discher, P. Janmey, P., and Y. L. Wang. Tissue cells feel and respond to the stiffness of their substrate. *Science* **310**, 2005, pp. 1139-1143.

[2] D. T. Butcher, T. Alliston, and V. M. Weaver. A tense situation: forcing tumour progression. *Nat. Rev. Cancer* **9**, 2009, pp. 108-122.

[3] M. Eastwood, V. C. Mudera, D. A. McGrouther, and R. A. Brown. Effect of precise mechanical loading on fibroblast populated collagen lattices: morphological changes. *Cell Motil. Cytoskeleton* **39**, 1998, pp. 13-21.

[4] K. Hayakaya, N. Sato, and T. Obinata. Dynamic reorientation of cultures cells and stress fibers under mechanical stress from periodic stretching. *Exp. Cell Res.* **268**, 2001, pp. 104-114.

[5] R. De, A. Zemel, and S. A. Safran. Dynamics of cell orientation. *Nature Physics* **3**, 2007, pp. 655-659.

[6] A. Livne, E. Bouchbinder, and B. Geiger. Cell reorientation under cyclic stretching. *Nat. Commun.* **5**, 2014, pp. 3938.

[7] G. K. Xu, B. Li, X. Q. Feng, and H. Gao. A Tensegrity Model of Cell Reorientation on Cyclically Stretched Substrates. *Biophys. J.* **111**, 2016, pp. 1478-1486.