Advances in Applied Mathematics and Mechanics
Adv. Appl. Math. Mech., Vol. **14**, No. 1, pp. 79-100

DOI: 10.4208/aamm.OA-2020-0357
February 2022

Characterising Mechanical Properties of Flowing Microcapsules Using a Deep Convolutional Neural Network

T. Lin[1], Z. Wang[2], R. X. Lu[1], W. Wang[1] and Y. Sui[1,*]

[1] *School of Engineering and Materials Science, Queen Mary University of London, London E1 4NS, United Kingdom*
[2] *Department of Mechanical Engineering, University College London, London WC1E 6BT, United Kingdom*

Received 18 November 2020; Accepted (in revised version) 17 January 2021

Abstract. Deformable microcapsules are widely used in industries and also serve as a mechanical model of living biological cells. In this study, we develop a novel method, by integrating a deep convolutional neural network (DCNN) with high-fidelity mechanistic capsule modelling, to identify the membrane constitutive law and estimate associated parameters of a microcapsule from its steady deformed profile in a capillary tube. Compared with conventional inverse methods, the present approach is more accurate and can increase the prediction throughput rate by a few orders of magnitude. It can process capsules with large deformation in inertial flows. Furthermore, the method can predict the capsule membrane shear elasticity, area dilatation modulus and initial inflation from a single steady capsule profile. We explore the mechanism that the DCNN makes decisions by considering its feature maps, and discuss their potential implication on the development of inverse methods. The present method provides a promising tool which may enable high-throughput mechanical characterisation of microcapsules and biological cells in microfluidic flows.

AMS subject classifications: 92C10, 76Z99

Key words: Microcapsules, flow cytometry, deep convolutional neural network, high throughput, mechanical characterisation.

1 Introduction

A capsule consists of a liquid droplet enclosed by a thin elastic membrane [1]. Microcapsules are widely used in food, cosmetic, biomedical and pharmaceutical industries

*Corresponding author.
Email: y.sui@qmul.ac.uk (Y. Sui)

 ©2022 Global Science Press

in a vast range of applications such as controlled agent release [2], targeted drug delivery [3], and encapsulated cell culture [4]. The capsule membrane protects its internal contents and regulates mass exchange, therefore knowing its mechanical properties is crucial in the design and fabrication of capsules. Microcapsules have also been widely used as a mechanical model of living biological cells [5–7]. The capsule elasticity, inferred from overall cell deformation, can be employed as a marker-free way to quantify the cell states and properties, such as the metastatic potential and degree of differentiation [8]. It therefore has many ground-breaking biological and clinical applications [9,10].

It has been very challenging to characterise the mechanical properties of microcapsules and biological cells due to their small size and fragility. A few methods have been proposed, such as the parallel plate squeezing [11], micropipette aspiration [12], optical stretching [13] and AFM measurement [14]. It is also possible to deform capsules using viscous fluid force that can be generated in shear [15, 16], centrifugal [17, 18], and extensional [19,20] flows. Those methods measure the deformation of capsules or cells under well-defined stress. Their throughput rates are typically limited to 100 capsules or cells per hour, which may be low for many important applications, such as cancer diagnosis or cell sorting based on cell mechanical properties. Those applications need to measure many thousands to millions of cells in minutes to hours, and therefore require high-throughput methods capable of processing at least hundreds of cells per second [21].

In recent years, a novel hydrodynamic approach with a much higher throughput rate has been proposed. In this method, microcapsules or biological cells are flowed through a microfluidic channel with comparable cross-sectional dimension, where they are deformed by the viscous fluid force. By fitting the steady deformed capsule profile to computational or theoretical predictions, one can inversely infer the membrane mechanical law and associated parameters. This promising approach has been developed for both artificial microcapsules [22–24] and living biological cells [6,8,9,25,26]. The state-of-the-art system can perform real-time processing of the deformation of hundreds of cells per second. However, the cell mechanical properties need to be calculated through post-processing, due to the long processing time of inverse methods.

Recently, deep neural networks have attracted much attention in a wide range of applications, for it provides a versatile method to infer the relationship between data and their corresponding measurements. In particular, the convolutional neural networks have significant merits in processing data that comes in the form of images [27], and have led to ground-breaking applications in image processing [28], classification of cells [29], geometrical optimization of aerofoils [30], and turbulence research [31–33].

In the present study, we for the first time integrate a deep convolutional neural network (DCNN) with high fidelity mechanistic modelling to create a novel approach to identify the membrane constitutive law and estimate associated parameters of a microcapsule from its steady deformed profile when flowing in a capillary tube. Unlike conventional inverse methods which need to identify the best fit online, the present DCNN is trained offline, and its prediction process only involves a limited number of algebraic calculations. It is therefore much faster and can predict the properties of more than one