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Mechanical and electrical numerical analysis of soft liquid-embedded deformation sensors analysis

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ABSTRACT

Soft sensors comprising a flexible matrix with embedded circuit elements can undergo large deformations while maintaining adequate performance. These devices have attracted considerable interest for their ability to be integrated with the human body and have enabled the design of skin-like health monitoring devices, sensing suits, and soft active orthotics. Numerical tools are needed to facilitate the development and optimization of these systems. In this letter, we introduce a 3D finite element-based numerical tool to simultaneously characterize the mechanical and electrical response of fluid-embedded soft sensors of arbitrary shape, subjected to any loading. First, we quantitatively verified the numerical approach by comparing simulation and experimental results of a dog-bone shaped sensor subjected to uniaxial stretch and local compression. Then, we demonstrate the power of the numerical tool by examining a number of different loading conditions. We expect this work will open the door for further design of complex and optimal soft sensors.

While engineering applications often use stiff and rigid materials, soft materials like elastomers enable the design of a new class of electronic devices that are flexible, stretchable, adaptive and can therefore be easily integrated with the human body [1–6]. These include highly conformable and extensible deformation sensors made from flexible substrates with embedded circuit elements, such as graphene sheets [7], nanotubes [8], interlocking nanofibres [9], serpentine patterned nanomembranes of Si [3,10,11], and conductive liquid micro channels [12–14].

A key feature of these sensors is their ability to reversibly stretch, bend, compress and twist to a great extent. Such deformations result in changes of the electrical resistance of the sensors, which are then used to determine the applied loading conditions. Therefore, the design of the next generation of soft sensors requires the development of numerical tools capable of predicting not only their mechanical performances [15,16], but also their electrical response. Such tools will enable the design of optimized sensors that are sensitive to desired loading conditions and also provide crucial insights into the working principles of these soft devices.

In this letter, we propose a 3D finite element-based numerical tool that predicts both the mechanical and electrical response of arbitrary shaped soft sensors subjected to any loading condition. In particular, we focus on sensors comprising an elastomeric matrix embedded with a network of channels filled with a conductive liquid [12–14], but the numerical approach can be easily extended to other types of soft sensors. The analyses are performed using the commercial finite element (FE) code Abaqus, which is an

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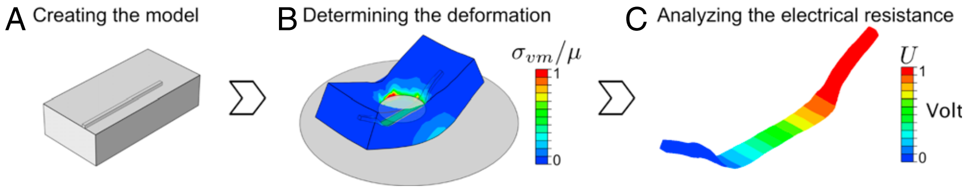

Fig. 1. The proposed FE-based numerical tool consists of three steps. (A) The model is created using CAD software and then meshed. (B) The deformation of the sensor is determined by using non-linear FE analysis, in which the contours show the normalized Von Mises stress σ_{vm}. (C) The resistance at different levels of deformation is obtained by performing a steady-state linear electrical conductivity analysis. The contours show the potential across the channel.

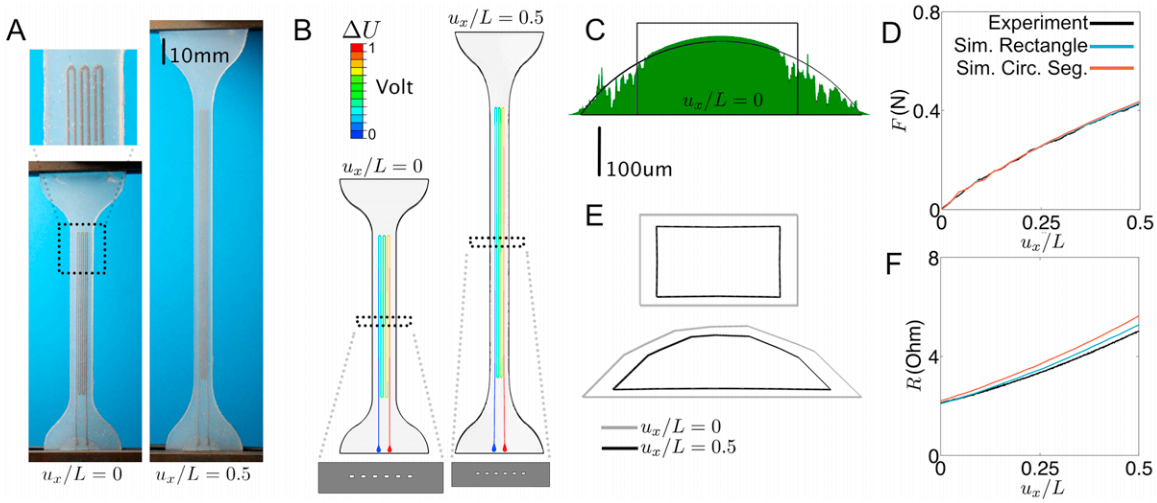

Fig. 2. Uniaxial extension of a dog-bone shaped soft sensor. (A) Experimental images of the undeformed ($u_x/L = 0$) and deformed ($u_x/L = 0.5$) sensor. (B) Numerical images of the undeformed ($u_x/L = 0$) and deformed ($u_x/L = 0.5$) sensor. The contours in the snapshot show the distribution of the electrical potential. (C) Cross-sectional profile measured with a laser interferometer (green) and cross-sections used in simulations. (D) Reaction force obtained in experiments and simulations as a function of the applied strain. (E) Cross-sections of the undeformed and deformed ($u_x/L = 0.5$) channels as predicted by the FE analysis. (F) Electrical resistance measured in experiments and simulations as a function of the applied strain.

attractive platform because it is well-known, widely available and particularly suitable for analyses involving large deformations. By making our code available online, we expect the proposed tool to be widely used and expanded to design more complex soft sensors with new and improved functions.

Our FE-based numerical tool consists of three steps, as indicated in Fig. 1 (the Abaqus script files and Matlab files used for our analysis are available online as Supporting Information):

Step A: Creating the model. A 3D model comprising both the flexible matrix and the circuit elements is first created using CAD software and then meshed. In particular, for the case of liquid-embedded soft sensors considered in this letter, the elastomeric matrix is meshed using linear tetrahedral elements (Abaqus element type *C3D4*), while a solid mesh of the channels is not created. In fact, only the surface mesh of the channel will be used to apply the pressure exerted by the fluid to the elastomer.

Step B: Determining the deformation. To determine the deformation of the sensor under specific loading conditions, a non-linear FE analysis is performed using the commercial package Abaqus/Explicit (v6.12). In the simulations, we fully account for contact between all faces of the model and ensure quasi-static conditions by monitoring the kinetic energy and introducing a small damping factor. For the case of liquid-embedded sensors investigated here, the response of the flexible matrix is captured using a nearly incompressible neo-Hookean material characterized by an initial shear modulus μ. Moreover, we consider the channels to be completely filled with a nearly incompressible fluid with bulk modulus $K = 100\mu$ and use the surface-based fluid cavity capability in Abaqus, so that the pressure applied by the fluid to the surface of the channel is determined from the cavity volume.

Step C: Analyzing the electrical resistance. To determine the electrical resistance of the deformed sensor, an isothermal steady-state linear electrical conductivity analysis (Abaqus step *Coupled thermal–electrical*) is performed on the deformed solid mesh of the circuit elements. Assuming the circuit elements are made of a material with electrical resistivity ρ, an electrical potential difference ΔU is applied between the two ends of the deformed circuit mesh and the dissipated work (W) over a time period of Δt is calculated. The electrical resistance of the channel (R) is then obtained as

$$R = \frac{\Delta U^2 \Delta t}{W}.$$