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Stretchable electronic devices for wearable and on-skin applications: effects of material anisotropy and extensibility in simple stretchable systems

Donato Di Vito(1), Teemu Salo(1), Jukka Vanhala(1) and Matti Mäntysalo(1)
(1) Faculty of Information Technology and Communication Sciences, Tampere University, Tampere, Finland. E-mail: donato.divito@tuni.fi

Abstract

Stretchable electronics pose a great challenge for electrical designers since mechanical interaction between the parts of these platforms should be properly taken into account and cannot be neglected. This work represents an effort to highlight some mechanical effects related to the use of anisotropic components in this type of electronics; by developing separate finite element models for both textile and on-skin electronics, the authors aim to discuss mainly the effects of material orientation and limiting extensibility in the substrates used, which can heavily affect the electromechanical performance of printed stretchable electronic devices.

1 Introduction

The development of novel sensors based on microfluidic and flexible electronic devices has brought a major boost in the range of applications available for personal electronics [1]. Within this framework, recent advances in printed stretchable electronics and the possibility to fabricate these devices as fully conformal and unobtrusive [2] makes printed electronics a viable option for a wide range of health tracking applications. Moreover, their additional characteristics related to low production costs and flexibility in the fabrication process makes them easy to integrate in several environments, such as textile [3], on-skin [1] and soft robots [4].

However, said devices are required to withstand a multitude of complex biophysical conditions. In fact, they have to keep their functionality under a range of operating temperatures and be biologically inert, while keeping a good quality and sampling frequency of the measured signals [2]. Even under a mechanical point of view, stretchable devices may be subjected to (and thus should tolerate) complex conditions, which may vary in terms of maximum applied deformation, number of cycles to withstand or type of deformation applied.

The variability of mechanical conditions applicable on these devices increases even more when considering that often, the devices are fabricated or applied onto anisotropic materials. As an example, both human skin [5] and knitted fabrics [3] , typically used in sports garments, have mechanical properties that not only depend on the deformation applied, but that also vary with their orientation. This further complicates the problem posed to the electrical designer and the variables in play when designing such stretchable devices. Taking into account the importance of unobtrusiveness for these applications further complicates these considerations, and thus the need to both miniaturize structures and closely match the mechanical properties of the electronic device and the underlying rest of the system becomes especially important.

Consequently, this work focuses on analyzing the mechanical behavior of simple printed, stretchable electronic devices that are either printed on laminated, knitted fabric or on thin TPU films to be mounted on human skin, from a computational standpoint. This is done by performing quasi-static FE analyses on a generic configuration for a simple section of a stretchable electronic device, consisting only of (i) a surface-mounted device (SMD), (ii) a conductive ink trace and (iii) a substrate, which in turn is considered to be anisotropic. The use of different material parameters, based on the mechanical properties of materials such as TPU-laminated stretchable textiles, as well as skin, allows to highlight certain specific behaviors that directly depend on the substrate used, showing how important it is to consider also the target application at the electrical design level.

2 Finite Element Analyses

The models of the considered stretchable electronic devices are illustrated in Figure 1. The device itself, considered to have the same design in all the simulations, is constituted by three different components: a surface-mounted device (zero-ohm resistor, size 0805), a conductive ink and a substrate, whose properties are covered in previous publications [6]–[8]. Depending on the type of model, boundary conditions or the type of properties used in the model were modified to match the specific material configuration analyzed, as explained more in detail later in this section.

The mechanical properties of both the knitted substrate and the skin are modelled using the simplified version of the anisotropic hyperelastic strain energy potential from the Holzapfel-Gasser-Ogden model [9]:

$$W = C_{01}(I_1 - 3) + \frac{k_1}{2k_2}\left(e^{k_2[\kappa I_1 + (1-3\kappa)I_4 - 1]^2} - 1\right) \quad (1)$$

where I_1 is the first deviatoric strain invariant, I_4 is a pseudo-invariant related to the fiber orientation in the

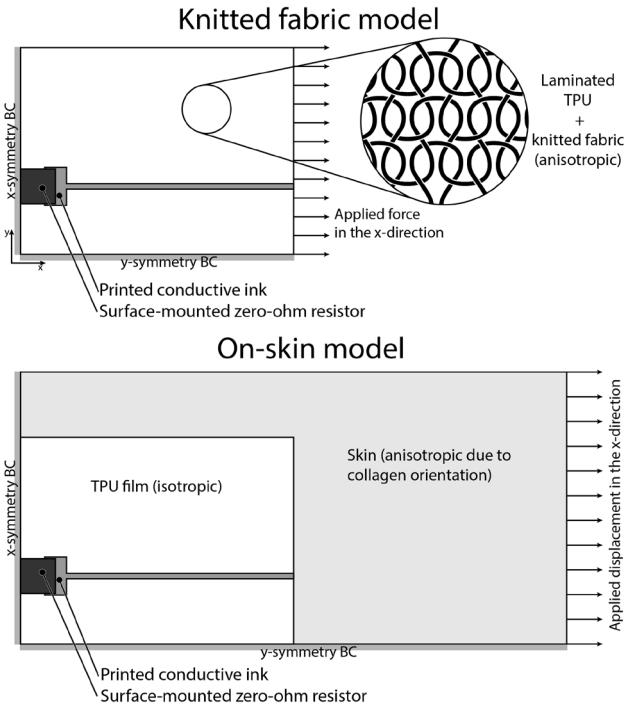

Figure 1. Schematic representation of the FE models considered.

material, while the parameters C_{01}, k_1, k_2 and κ define the material properties of the material depending on both the fabric used and its weaving pattern, or the collagen configuration in the case of skin. In particular, the parameter κ is considered to be equal to 0 for the knitted fabric [10], in order to simulate a monodispersed orientation distribution of fiber configuration in the medium, while κ is considered to be equal to 0.1535 for the skin model, since the collagen fibers are considered to have a specific distribution of orientation in the skin layer [9]. However, in the case of on-skin model, the TPU substrate is instead assumed to be in perfect contact with the underlying skin, which is modeled as 2 mm thick.

Both the results from the fabric model and the on-skin model were calculated applying the same types of boundary conditions, and the results were obtained considering the stretchable electronic system aligned along the principal axis of the underlying material or transversely to it, in order to highlight the differences arising because of anisotropy and of limited extensibility in the principal direction. In the case of the on-skin model, the two different orientations represent the application of the stretchable electronic device along or transversely to the Langer lines [11].

All the models were first tested to achieve the same level of average true strain on the stretchable substrate (equal to 0.20) in the *x*-direction. Based on the applied loads, the models having the principal material direction transverse to the load were tested using the same applied force registered on the corresponding axial model. Due to the nonlinear behavior assumed for hyperelastic anisotropic materials, the system response was analyzed at different steps during the load application by performing additional analyses for comparable levels of load or applied displacement, depending on the specific case.

Table 1. Parameters used to model the mechanical behavior of knitted fabrics and skin.

Parameter	C01	k1	k2	κ
Knitted fabric [10]	0.64 MPa	0.12 MPa	0.52	0
Skin [12]	0.1007 MPa	24.53 MPa	0.1327	0.1535

3 Results and discussion

A significant parameter in the analysis of the electromechanical behavior of stretchable electronic materials is the behavior of the conductive line itself. As shown in previous works [6], in fact, this behavior can be related to both the increase in electrical resistance of the system and to its maximum deformation at failure. Consequently, the deformation of conductive lines in the different systems has been thoroughly analyzed to highlight the main differences in behavior and generalize some concepts related to the behavior of stretchable electronic devices on anisotropic systems.

When reaching the same levels of overall deformation, both the knitted textile and the on-skin model show roughly the same levels of deformation in the conductive line, especially in regions further away from the SMD.

3.1 Knitted fabric system

Figure 2 shows the force-displacement behavior of the knitted fabric system with the principal material direction aligned in the same direction (blue curve) or transversely to the direction of applied load (orange curve). As expected, anisotropic properties of the material generate a different response in the two systems for the same load applied. For the three force stamps shown (at 5 N, 15 N and 25 N) it is possible to notice that not only is the force response different, but also the deformation behavior attained at different load levels. As shown by the histograms in Figure 2, in fact, with the increase in the applied load the difference in the overall strain distribution along the conductive trace becomes more and more prominent, due to the anisotropic mechanical behavior of the substrate, which makes it respond to the external stimulus with a different behavior when loaded in different directions.

It is also possible to notice that, for increasing values of applied load, the stiffness of the two models (simply defined as the pointwise slope of the load-displacement curves obtained) starts to change dramatically at around 20 N for the parallel-oriented knitted substrate, while the same does not happen for the orthogonal one. This behavior, which is related to the limiting extensibility of the material, occurs when the material fibers in the knitted substrate start to orient in the loading direction and actively participate to carrying the applied load. Mechanically, this translates in aquick material stiffening in a specific direction, which may lead to a limitation on the maximum strain achievable under the application of an external load. In turn, this causes a change in the distribution of strain

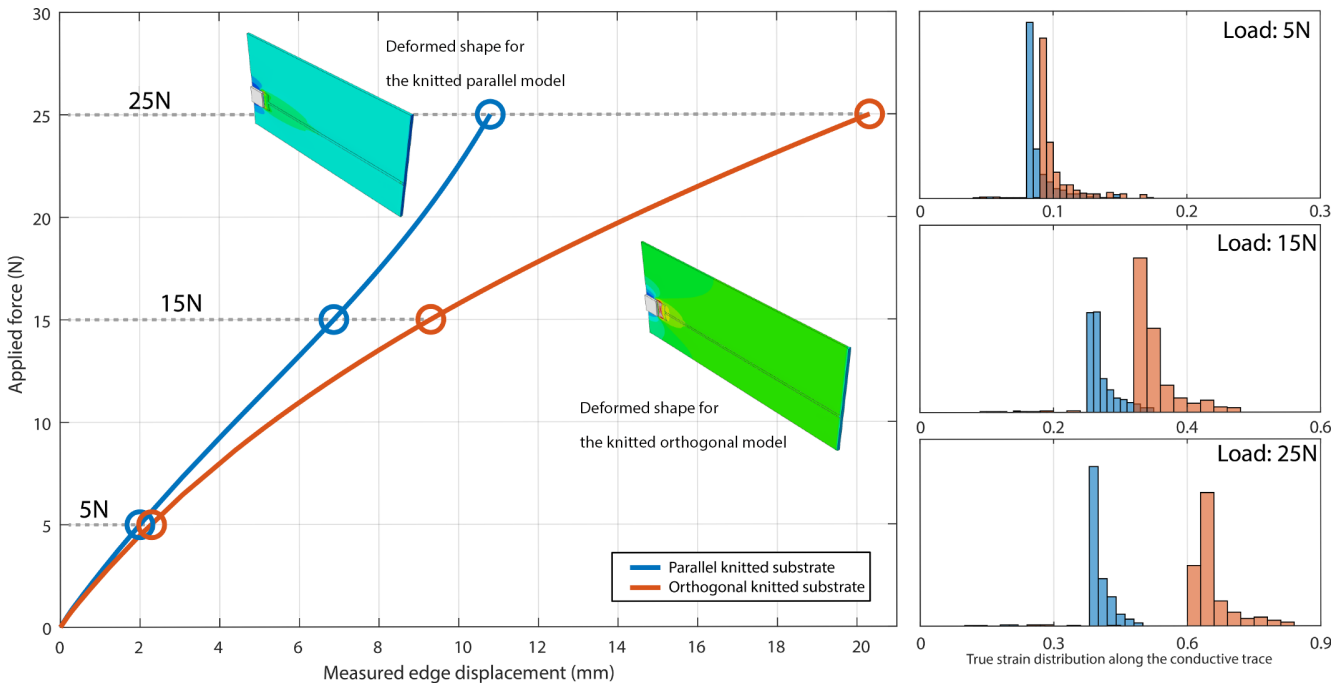

Figure 2. Left: Applied force-registered displacement curve (and related deformed shapes at 25 N) obtained for the knitted parallel and orthogonal model. It is possible to see the difference in mechanical behavior due to the different material orientation; right: histograms that show the longitudinal strain distribution on the printed conductive lines the two colors refer to the legend in the figure on the right.

along the conductive line since its maximum achievable deformation becomes limited by the substrate.

3.2 On-skin system

The on-skin system has a different general response to the external loads applied. In fact, as can be seen from Figure 3, the response obtained by aligning the stretchable device along or transversely to the loading directions changes dramatically in terms of both deformation along the conductive line and region that achieves maximum strain. In fact, while for the transversely aligned model the maximum level of strain is attained at a few millimeters from the beginning of the conductive line, maximum strain in the axially aligned model show that the highest levels of strain are achieved in the interconnect region, while the deformation of the conductive line remains mostly constant. This specific behavior, traceable to the lower level of maximum extensibility achievable on skin than in knitted fabric. In fact, regions closer to the maximum extensibility of skin respond to external loads with a stiffer behavior, and this causes the strain to localize more closely to rigid inhomogeneities, such as the SMD.

This causes higher strains at the interconnect level and, more importantly, may result in high levels of shear strain

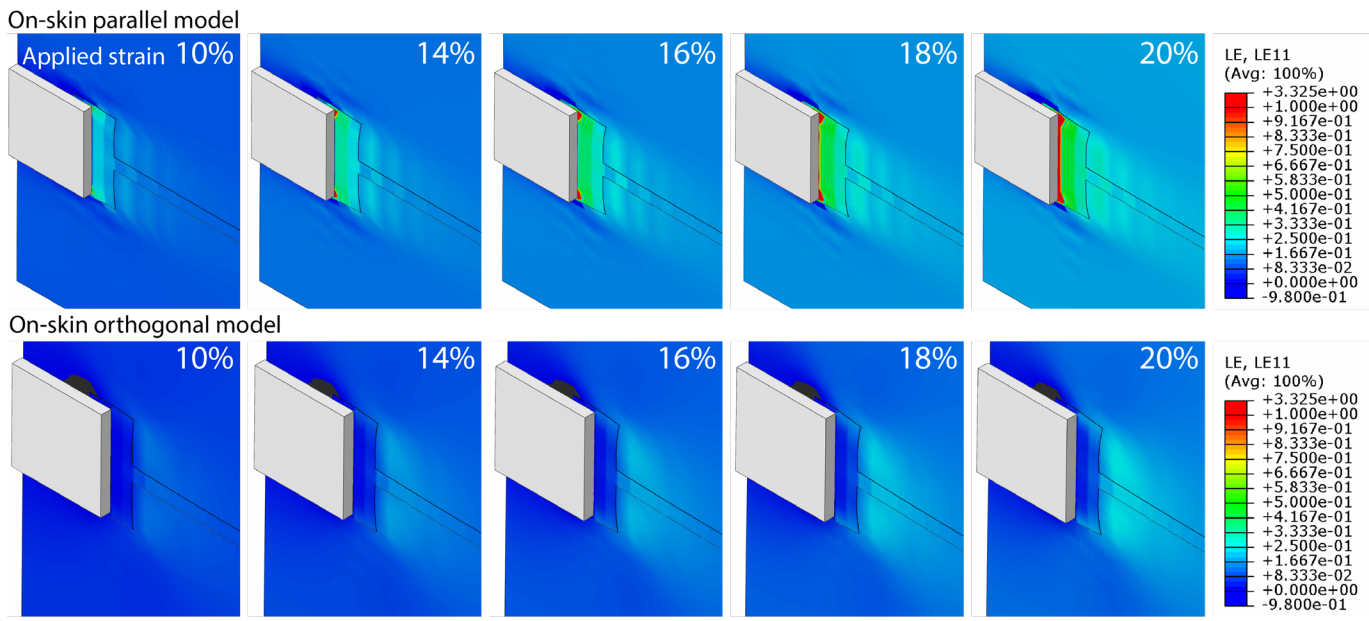

Figure 3. Plots for the axial deformation in the loading direction (LE11) in the on-skin models at different levels of applied strain. The deformation buildup at the SMD-interconnect (red region) is evident, while the levels of strain in the orthogonal models are generally lower.

at the interface between the rigid component and the interconnect, where generally isotropically or anisotropically conductive adhesive are used. The effect of these shear strains can be detrimental on the performance of this material, both under an electrical and mechanical point of view: in fact, while the quality of the electrical connection can suffer from these types of strains already at low levels of deformation, higher levels of shear can cause nucleation of cracks at the interface and, consequently, crack propagation and debonding at the interface level between the rigid and deformable components of the system.

4 Conclusions

Current development of stretchable electronics allows to fabricate electrical devices with a wide range of potential applications, going from sensing in different conditions to actuating movements of robotic parts. Within this context, a proper knowledge in terms of material properties allows to improve even more the current range of use cases. Employing material characteristics such as limiting extensibility of a material, as well as mechanical anisotropy, may allow to tailor even more the electromechanical properties of a stretchable device to focus on specific use cases.

However, introduction of additional degrees of freedom, such as the aforementioned ones, should be carefully planned and studied. As we saw with the on-skin models in this work, in fact, change of mechanical properties and substrate strain-induced stiffening may lead to a complete change in mechanical behavior of the system. In turn, this can change the electromechanical behavior of the system, causing the development of unexpected failure mechanisms, such as debonding between components of the system due to high levels of shear strains. Sudden changes in mechanical behavior, thus, may increase the probability of a previously unforeseen failure mechanisms. In order to take them into account, more efforts should be spent on both numerical and experimental analyses on stretchable electronics in order to better define the cause-effect relationships between local material properties and the overall electromechanical behavior of these devices.

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