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INTRODUCTION OF HUMAN SKIN PRESTRESS: EFFECT ON THE WAVE PROPAGATION VELOCITY

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Abstract. *The present paper proposes an insight into the characterization of an intrinsic human skin characteristic, which is the natural prestress of the cutaneous tissue. The aim of this work is to develop a 3D model based on the Finite Element Method (FEM) in order to quantify the natural prestress of the human skin. To this aim, the upper outer surface of a stratified 3D volume of skin is subjected to a mechanical impact. The cutaneous tissue is considered as an isotropic linear elastic material. The wave propagation velocity is calculated along a path on the surface of the FE model. The influence of the human skin prestress on the velocity of the wave propagation is investigated. A major conclusion states that the prestress slows down the wave propagation. Thus, the wave propagation velocity decreases when the prestress increases.*

Keywords: *Natural prestress, Human skin, FE Model, wave propagation, Impact.*

1. Introduction

The human skin is an important organ in our bodies which represents our first contact with our environment. It ensures protective and exchanging functions (Agache 2000). From a mechanical point of view, the human skin is a heterogeneous material saturated by a physiological fluid with three layers. His material is assumed to be viscoelastic anisotropic behavior with a natural pre-stress (Leveque et al., 1980; De Rigal et al., 1985). The characterization of the mechanical properties of human skin is of paramount importance. Many previous studies focused on the evaluation of human skin mechanical properties (Agache et al., 1980; Delalleau et al., 2008; Abellan et al., 2013, Bonnet et al., 2017). Among these mechanical properties, the quantification of the natural prestress that exists initially in the human skin is very important for a realistic description of the mechanical behaviour of the skin. In the bibliography, experimental devices were developed using an air jet to determine the intra-ocular pressure (Kawahara et al. 2006, Tanaka et al. 2007). Natural prestress of the skin is similar to this intra-ocular tension. In order to introduce the skin tension, we choose to subject the skin to an impact and follow the resulting wave. The wave propagation is considered as an experimental marker of the evolution of the mechanical properties of the cutaneous tissue. It can be followed both on the surface and in the volume of the skin. In order to identify the mechanical properties, many assumptions were considered. The skin was considered as a linear elastic material (Zahouani et al., 2009) or hyperelastic (Bischoff 2004). Extension to viscous phenomenon is proposed in (Flynn et al., 2011). In this study, we developed a FE numerical model on Abaqus / Explicit[®]. The wave propagation is followed so then we considered the skin to be a homogeneous, isotropic and elastic material taking into account the prestress. A validation of this model is presented using the Rayleigh wave propagation velocity on the surface of an elastic membrane (Danielson 1973, Diridollou et al. 2000). Different values of the prestress were considered. The resulting wave propagation velocity was calculated for each prestress value to identify the effect of prestress on the wave propagation velocity in the skin tissue. This paper presents the method in part 2, i.e. the FE model end its validation. Part 3 describes and discusses the numerical results. The fourth part is a conclusion.

2. Material and methods

2.1.FE method

A 3D FE numerical model is developed on Abaqus/Explicit[®] (Fig. 1). The geometry of the corresponding volume is a parallelepiped with the dimensions: $11.11 \times 100 \times 100 \text{ mm}^3$. A two layers skin is considered: epidermis and dermis for the upper layer (with a depth of 1.11 mm) and hypodermis for the lower layer (with a depth of 10mm). The material considered has an isotropic elastic behavior.

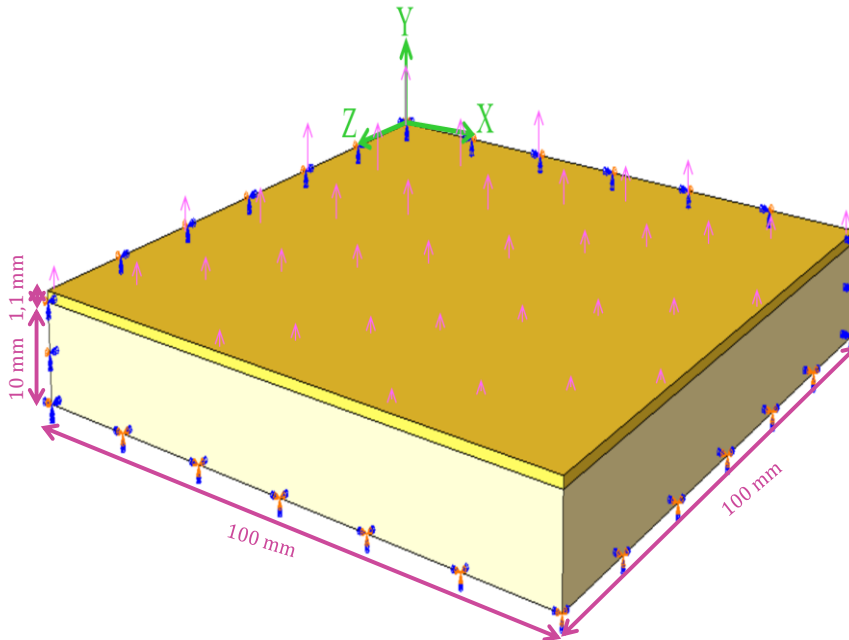


Fig. 1. FE numerical model

The skin is embedded at the bottom. A symmetry condition is imposed for the surfaces with the outgoing normal vectors $-\vec{e}_x$ and $-\vec{e}_z$. The surfaces with the outgoing normal vectors \vec{e}_x and \vec{e}_z are kept free. The test consists on an air jet impact imposed to the upper surface. This air jet impact is simulated with a pressure of 2 bars onto the upper surface of the skin with a Gaussian function.

The maximum value corresponds to the origin of the orthonormal coordinate system $(\vec{e}_x, \vec{e}_y, \vec{e}_z)$. The loading pressure is imposed during 1 ms then the pressure is stopped instantaneously and the wave propagation on the skin surface is followed during 10 ms (Fig. 12).

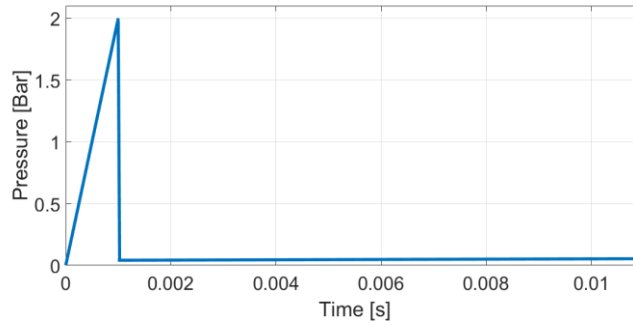


Fig. 2. Loading diagram

A 3D hexahedral linear element (C3D8R) was considered for the mesh with a total number of 110000 elements.

2.2. Wave propagation in elastic membrane

The skin is considered to be a homogeneous, isotropic A path is chosen on the upper surface of the FE model with respect to the direction of prestress that will be introduced afterwards. This choice is made in order to study the effect of the prestress on the wave propagation velocity in same direction of the imposed prestress. It starts from the central point of pressure application and follows an horizontal line till the edge of the surface (Fig. 3).

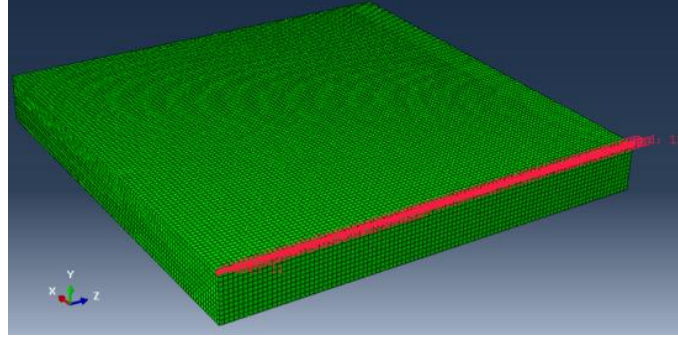


Fig. 3. The chosen path for calculus of the wave propagation velocity

The velocity of the wave propagation is calculated considering the displacement of skin surface between two increments. The wave velocity corresponds to the quotient: $\frac{\Delta z}{\Delta t}$, where Δz is the spatial difference between two crests and Δt is the time interval between the chosen increments.

2.3. FE model validation

The imposed air jet at the origin of the orthonormal coordinate system generates a wave both in the volume and at the surface of the skin. We consider the following material properties for our FE model: a Young modulus of $E = 200$ kPa and a Poisson coefficient $\nu = 0.48$. The wave velocity calculated through the chosen path, considering the quotient $\frac{\Delta z}{\Delta t}$, is: $V = 8\text{m/s}$.

In order to validate our FE model, we propose to evaluate the Rayleigh wave velocity along a chosen path V_R (Li et al. 2011):

$$V_R = \frac{0.87 + 1.12\nu}{1 + \nu} \sqrt{\frac{E}{2\rho(1 + \nu)}} \quad (1)$$

where ρ is the mass density of the skin. Considering $V_R = 8\text{m/s}$ and $\rho = 1000 \text{ Kg/m}^3$, we can calculate the Young modulus using (1). We found $E = 209.43 \text{ kPa}$. A small difference is found between the calculated value of Young modulus and the one introduced in the FE model ($E = 200 \text{ kPa}$). A small discrepancy of 4.7% is found between these two values. This could be due to the existence of other types of surface waves such as Love wave, which means that the wave velocity has two components: Rayleigh and Love waves. Therefore, we can validate our proposed FE model.

3. Results and discussion

Figure 4 shows the displacement of human skin surface through the chosen path in the FE model.

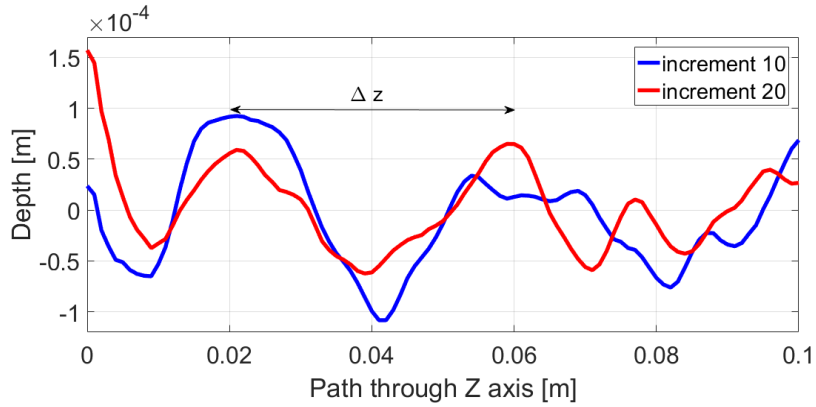


Fig. 4. The displacement of a free prestress human skin surface

In the first case, we consider the human skin is free from prestress (0 kPa of prestress). Then, the calculated velocity is $V = 8\text{m/s}$.

In the second case, we consider the same FE model and we add the prestress component in the upper layer of the model of the human skin. The prestress component is introduced using the predefined field modulus in Abaqus[®]. This component corresponds to the initial prestress existing in the human skin which represents the fibres network pretention. The prestress is introduced through the directions \vec{e}_x and \vec{e}_z and it is equal in both of them. The considered values of pre-

stress are: 1, 5, 10, 15 and 20 kPa. The considered Young modulus is $E = 200$ kPa and the Poisson coefficient is $\nu = 0.48$.

We calculate the wave velocity through the same path between two increments.

Table 1. The wave propagation velocity in the human skin surface for a prestressed skin

<i>Prestress [kPa]</i>	<i>Wave velocity [m/s]</i>
0	8
1	5.6
5	4.8
10	4.4
15	4
20	4

Table 1 shows that the prestress and the propagation speed of the wave vary inversely. In other words, the wave propagation velocity decreases as prestress increases and vice versa. Prestress represents an obstacle to the propagation of the wave. In this case, the skin subjected to prestress is similar to a trampoline and absorbs the load applied to it. The wave is then braked and damped, which means that its propagation speed and amplitude decrease.

4. Conclusion

In this work, we introduced an important property of the cutaneous tissue, which is the natural prestress existing in human skin. A 3D FE numerical model was developed using Abaqus/Explicit[®] that simulates an impact test with an air jet. The skin was considered as a homogeneous linear elastic isotropic material. The impact generates a wave which propagates on the surface of the skin. The model was validated by identifying the Young modulus from the analytical analysis of the Rayleigh wave propagation velocity.

The prestress was introduced in the numerical model according to two lateral directions considering a given value of Young modulus E and Poisson ratio ν . A panel of different prestress values was considered. From the obtained velocities, it is possible to conclude that the propagation velocity decreases when the prestress increases.

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