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Short communication

Biomechanical response of varicose veins to elastic compression: A numerical study

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ABSTRACT

A patient-specific finite-element (FE) model of the human leg is developed to model the stress distribution in and around a vein wall in order to determine the biomechanical response of varicose veins to compression treatment. The aim is to investigate the relationship between the local pressure on the soft tissues induced by wearing the compression garment and the development and evolution of varicose veins and various skin-related diseases such as varicose veins and ulcers. Because experimental data on the mechanical properties of healthy superficial veins and varicose veins are scarce in literature, ultrasound images of *in vivo* varicose veins are acquired and analysed to extract the material constants using Finite Element Model Updating. The decrease in trans-mural pressure, which conditions the effectiveness of compressive treatments, is computed from the simulation results. This constitutes the original added value of the developed model as decrease in trans-mural pressures cannot be assessed experimentally by any other means. Results show that external compression is effective in decreasing the trans-mural pressure, thereby having a positive effect in the control and treatment of vein-related diseases.

1. Introduction

Compression therapy by Medical Compression Stockings (MCS), which is considered as the "gold standard" therapy for venous insufficiency, has been a topic of important research for 30 years. The following effects or actions of MCS have gained a special interest:

Hemodynamic effects: Mayberry et al., (1991), Ibegbuna et al., (2003), Guesdon et al., (2007), Downie et al., (2008) and Wang et al., (2012), in continuation of pioneer studies on collapsible tubes: Katz et al., (1969), Moreno et al., (1970) and Kamm and Shapiro, (1979),

Clinical and post-surgery effects: Nehler et al., 1992, (1993), Kern et al., (2007), Villavicencio, (2009) and Hamel-Desnos et al., (2010),

Skin and deep tissue compression: Wildin et al., (1998), Agu et al., (1999), (Best et al., 2000), Yeung et al., (2004), Liu et al., (2005), Gaied et al., (2006), Liu et al., (2006), Dai et al., (2007), Lee and Han, (2010), Martinez et al., (2010), Avril et al., (2010) and Dubuis et al., (2012).

However, some of the mechanisms by which MCS act are still not clearly understood. The present study aims at addressing the effect of MCS on varicose veins by adopting a finite-element modelling approach.

2. Materials and methods

2.1. Imaging methods

Images are acquired on the calf of a 50 year old male patient with a varicose vein:

Magnetic resonance imaging is applied with a two dimensional T1 TSE modality on a Siemens 1.5T scanner using pixel resolution: $0.7813 \times 0.7813\ \text{mm}^2$ and slice thickness: 3.9 mm.

Echography is applied for obtaining images with a better spatial resolution in the region of the varicose vein. The ultrasound images are acquired with and without 15–20 mmHg MCS (AFNOR, 1986) both in the standing and supine position (Fig. 1).

2.2. Finite element model

2.2.1. Finite element mesh

The geometry is reconstructed from both MRI (deep tissues) and ultrasound scans (vein). The meshing tools available in ABAQUS® are used to generate the computational mesh of the reconstructed geometry (Fig. 2). Continuum plane strain elements with a hybrid formulation are used for the muscle, fat and vein

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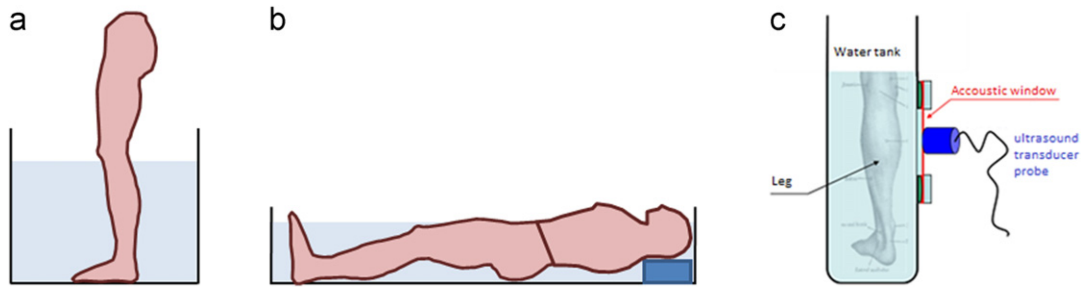

Fig. 1. Acquisition of echographic images both in the standing and supine position (a and b). A special precaution was taken as illustrated in panel c.

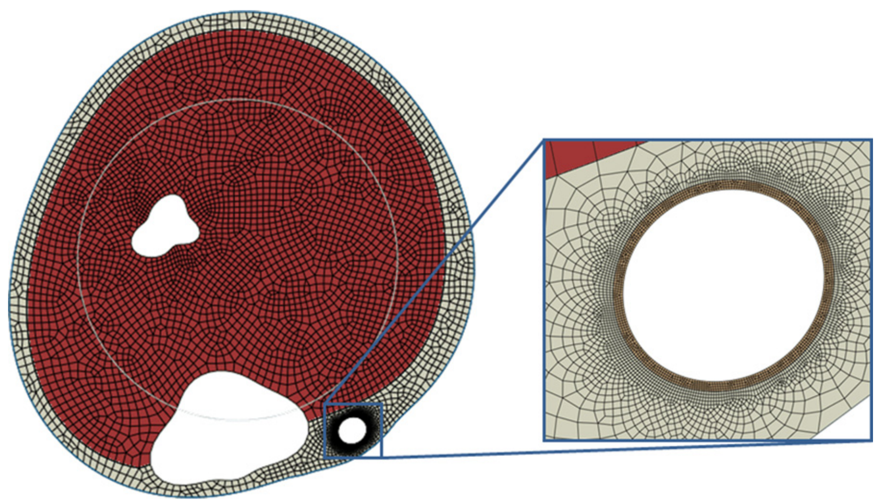

Fig. 2. Finite element mesh of the 2D patient specific mesh. It consists of continuum plane strain elements for the muscle, fat and vein wall and truss elements for the muscular aponeurosis, skin and MCS. A relatively finer discretisation is used in the vicinity of the vein wall. The thickness-to-radius ratio of the vein is taken as 0.1, as reported in the literature.

wall. A 2-D model is used since Avril et al., (2010) showed that the 2-D approach predicts a similar pressure distribution in the calf tissues as a full 3-D model.

A hybrid formulation is preferred because the soft tissues are defined as quasi-incompressible (Poisson's ratio >0.475). Truss elements are used for the discretisation of the muscular aponeurosis, the skin and the MCS. A relatively finer discretisation is used around the vein. The models contain about 13 600 elements and 33 800 degrees of freedom (including the Lagrange multiplier variables). A mesh convergence study was conducted showing that further mesh refinement produces a negligible change in the solution.

2.2.2. *Internal blood pressure in the vein*

The intravascular pressure is accounted for by a constant pressure applied on the inner surface of the vein wall. The pressure imposed is 15 mmHg in the supine position and 90 mmHg in the standing position. This pressure is responsible for an initial pre-stress of the vein wall before applying compression, which is considered by applying an initial circumferential pre-stress on the vein wall to counterbalance this pressure. The value of the circumferential pre-stress in each element of the vein wall is determined by applying the Laplace law. A 1 kPa pre-stress is also defined on the skin in the circumferential direction (Flynn et al., 2011).

2.2.3. *Boundary conditions*

The tibia and fibula are fixed in this model.

2.2.4. *Contact pressure on the skin.*

The interaction between the skin and the sock is enforced using the default ABAQUS® parameters in the normal direction (Table 1) and using a penalty method in the tangential direction. A skin-to-textile friction coefficient of 0.3 is used for the tangential direction, as reported in the literature (Gerhardt et al., 2009).

2.2.5. *Constitutive equations*

A summary is given in Table 2. A linearised model is preferred for the vein because (i) the developed biomechanical model is used to simulate the deformation of the leg between two states of loading (compressed and uncompressed) which are very close to one another, and (ii) we do not need to know the stress-free state of our leg as is the case with nonlinear material behaviour models. The Poisson's ratio is fixed at 0.49 (Wells and Liang, 2011) and two different stiffness values are identified, in supine and standing positions respectively, as the diameter reduction of the vein lumen, due to a 15–20 mmHg class compression sock, is 10% in the supine and 3% in the standing position.

2.2.6. *Analysis procedure*

Simulation is divided into 3 steps as previously described:

Step 1:Initial stress on vein wall and skin and blood pressure loading
Step 2:Inflate sock and activate the contact conditions between the skin and the sock
Step 3:Release the MCS and calculate the equilibrium position

The resolution is performed *via* an implicit scheme. The default convergence criteria in ABAQUS/standard are used (Table 1).

3. Results

3.1. *Mechanical properties of the vein wall and fat*

The FE model is calibrated against the echographic images of compressed and uncompressed legs acquired in the standing and supine positions. The identified Young's moduli for the vein wall are 100 kPa in the supine position and 836 kPa in the standing position. The identified C_{10} constant for the fat, characterising the shear modulus in the Neo-Hookean strain energy function, is 5 kPa.