



**HAL**  
open science

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

Pierre-Yves Rohan, Pierre Badel, Bertrand Lun, Didier Rastel, Stéphane Avril

### ► To cite this version:

Pierre-Yves Rohan, Pierre Badel, Bertrand Lun, Didier Rastel, Stéphane Avril. Biomechanical response of varicose veins to elastic compression: A numerical study.. *Journal of Biomechanics*, 2013, 46 (3), pp.599-603. 10.1016/j.jbiomech.2012.10.043 . hal-00801291

**HAL Id: hal-00801291**

**<https://hal.science/hal-00801291>**

Submitted on 15 Mar 2013

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25

# **Biomechanical response of varicose veins to elastic compression: a numerical study**

**Rohan C.P-Y.<sup>1</sup>, Badel P.<sup>1</sup>, Lun B.<sup>2</sup>, Rastel D.<sup>3</sup>, Avril S.<sup>1</sup>**

<sup>1</sup> Ecole Nationale Supérieure des Mines de Saint-Etienne, CIS-EMSE, CNRS:UMR5307, LGF, F-42023 Saint Etienne, France

<sup>2</sup> Sigvaris Research and Development Center, Saint-Just-Saint-Rambert, France

<sup>3</sup> Vascular physician, Grenoble, France

Corresponding author:  
Christian Pierre-Yves Rohan  
Center for Health Engineering  
Ecole Nationale Supérieure des Mines  
158 cours Fauriel  
42023 SAINT-ETIENNE CEDEX 2 France  
Phone: +33477426609  
Fax: +33477499755  
Email: [rohan@emse.fr](mailto:rohan@emse.fr)

Keywords: Varicose veins; trans-mural pressure; Finite Element Updating; Medical Compression Stockings

Word count (introduction through conclusion): 1 988

## 26 **Abstract**

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

40

# 41 Introduction

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

45 - hemodynamic effects: (Mayberry et al., 1991), (Ibegbuna et al., 2003), (Guesdon et al., 2007), (Downie et  
46 al., 2008) and (Wang et al., 2012), in continuation of pioneer studies on collapsible tubes: (Katz et al.,  
47 1969), (Moreno et al., 1970) and (Kamm and Shapiro, 1979);

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

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

53

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

56

# 57 **Materials and methods**

## 58 **-1- Imaging methods**

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

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

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

65

## 66 **-2- Finite Element Model**

### 67 *Finite element mesh*

68 The geometry is reconstructed from both MRI (deep tissues) and ultrasound scans (vein). The meshing  
69 tools available in ABAQUS® are used to generate the computational mesh of the reconstructed geometry  
70 (Fig. 2). Continuum plane strain elements with a hybrid formulation are used for the muscle, fat and vein  
71 wall. A 2-D model is used since (Avril et al., 2010) showed that the 2-D approach predicts a similar  
72 pressure distribution in the calf tissues as a full 3-D model.

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

78

### 79 *Internal blood pressure in the vein*

80 The intravascular pressure is accounted for by a constant pressure applied on the inner surface of the vein  
81 wall. The pressure imposed is 15mmHg in the supine position and 90mmHg in the standing position. This  
82 pressure is responsible for an initial pre-stress of the vein wall before applying compression, which is  
83 considered by applying an initial circumferential pre-stress on the vein wall to counterbalance this  
84 pressure. The value of the circumferential pre-stress in each element of the vein wall is determined by

85 applying the Laplace law. A 1 kPa pre-stress is also defined on the skin in the circumferential direction  
86 (Flynn et al., 2011).

87

### 88 *Boundary conditions*

89 The tibia and fibula are fixed in this model.

90

### 91 *Contact pressure on the skin.*

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

95

### 96 *Constitutive equations*

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

104

### 105 *Analysis procedure*

106 Simulation is divided into 3 steps as previously described:

107 *Step 1* Initial stress on vein wall and skin and blood pressure loading

108 *Step 2* Inflate sock and activate the contact conditions between the skin and the sock

109 *Step 3* Release the MCS and calculate the equilibrium position

110

111 The resolution is performed via an implicit scheme. The default convergence criteria in ABAQUS/Standard  
112 are used (Tab. 1).

113

# 114 Results

## 115 -1- Mechanical properties of the vein wall and fat

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

120

## 121 -2- Parametric study

122 Simulations are run corresponding to the supine and standing positions. Salient quantitative results of  
123 each simulation are reported in the Appendix through Table A1 to A7, where the influence of the  
124 following parameters is reported:

125 [a] Ratio of adipose tissue to leg size (Table A1);

126 [b] Position on the leg contour (Table A2);

127 [c] Vein lumen size (Table A3);

128 [d] Depth of vein in adipose tissue (Table A4);

129 [e] Effect of the applied external compression (Table A5);

130 [f] Influence of the "type" of fat (Table A6 for the influence of the stiffness and Table A7 for the  
131 influence of the incompressibility parameter).

132

133 Based on the results, it can be summarized that the biomechanical response of veins is subject to three  
134 main mechanical factors: the vein size, the local radius of curvature and the fat stiffness. This highlights  
135 the strong patient-specific response of the leg to external compression.

136

137 Parametric studies were also (run about) carried out on the element types, the type of contact and the  
138 type of material behaviour. Results (Tables A8 through A12) show that the modelling assumptions do not  
139 affect the trends (about) of the three main mechanical factors.

140

# 141 Discussion

## 142 -1- Material properties

143 The stiffness properties of the fat and of the vessel wall are identified by Finite Element Model Updating.  
144 The obtained values are consistent with values reported in the literature. In a study to determine the *in*  
145 *vitro* elastic properties of human saphenous vein segments, (Wesly et al., 1975) reported that the *in vitro*  
146 saphenous tangent modulus in the circumferential direction is considerably smaller at pressure ranges  
147 corresponding to **the** supine position (30 kPa and 65 kPa at 10 mmHg and 25 mmHg of pressure  
148 respectively) but is similar to carotid values at pressures similar to those encountered *in vivo* in the  
149 standing position (990 kPa and 1.5 MPa at 75 mmHg and 100 mmHg of pressure respectively). This is  
150 consistent with other studies, conducted both *in vivo* and *in vitro*, showing that veins exhibit a non-linear  
151 mechanical behaviour and become stiffer as **(it) they deform(s)**(Buhs et al., 1999) (Zhao et al., 2007). More  
152 recently, based on the material parameters reported by (Chuong and Fung, 1986), Han estimated the  
153 Young's modulus of blood vessels to be 100 kPa (Han, 2011). Material parameters of the Fung exponential  
154 strain energy function have also been reported for the human saphenous vein (Zhao et al., 2007) and for  
155 porcine jugular veins (Lee and Han, 2010). They are all comparable with the elastic properties found in  
156 our approach.

157  
158 The material parameter identified for the fat lies within the range of values reported **(by)** in a study  
159 involving six patients. (Dubuis et al., 2012)

160  
161 The fact that the narrowing of the vein is less pronounced in the standing position, for a given level of  
162 external compression, may also be due to the fact that the applied external pressure has to work against a  
163 higher internal blood pressure (Partsch and Partsch, 2005), (Partsch, 2007).

## 164 165 -2- Main trends

166 The results obtained using the proposed model show that hydrostatic pressure in fat **is (i) (is)** effectively  
167 increased and **(ii)** by an order of magnitude comparable to the mean contact pressure exerted by the MCS  
168 on the skin.

169



170 The computed hydrostatic pressure in the fat is essential to understanding how the pressure is transmitted  
171 through the superficial soft tissues. Moreover the increase in tissue pressure is regarded as a crucial  
172 mechanism (to the) in compressive treatments (Bergan, 2007). Clearly, appreciating how geometric and  
173 material parameters affect the transmission of pressure is an important step to understanding both the  
174 modes of action of EC treatment and the rationales behind its efficacy.

175

176 Other research teams have reported satisfactory results for the measurement of vein deformation under  
177 compression (Partsch et al., 2010) but have not used these results for quantifying the trans-mural  
178 pressures. The results of our model indicate that 15-20 mmHg MCS are effective in decreasing the trans-  
179 mural pressure on vein walls. The values predicted are twice as high in the standing position than in the  
180 supine position. This trend corroborates that reported *in vitro* by (Gardon-Mollard and Ramel, 2008).

181

182       **-3- Clinical relevance**

183 From a clinical perspective, an increase of the trans-mural pressure **on** varicose vein walls exacerbates the  
184 disease and the underlying Chronic Venous Insufficiency (CVI). The goal of compression therapy is to  
185 restore a trans-mural pressure **which is** as normal as possible, by increasing the perivenous tissue  
186 pressure (Gardon-Mollard and Ramel, 2008). The results reported here confirm the idea that MCS work  
187 towards reducing the trans-mural pressure. In addition, trans-mural pressure is known to be related to  
188 the tension of the vein wall according to the Laplace law (Gusic et al., 2005). Reduction of the tension  
189 implies a smaller number of alterations in the vein wall associated with various pathologies. Another  
190 consequence is a greater stability with respect to axial buckling and tortuosity development (Han,  
191 2007)(Han, 2009)(Han, 2012).

192

193 The action of MCS may also affect the remodelling of the vein. (Travers et al., 1996) **(have)** observed that  
194 varicose saphenous veins contained significantly higher amounts of collagen in all layers of the vein wall  
195 and that these collagen fibres were seen to invade and break up regular muscle layers of the media in  
196 varicosis. Reduction of the tension in the vein wall under the action of MCS is prone to hinder these  
197 effects.

198

199 Another **important** clinical **(important)** aspect concerns the evolution of CVI more generally: because **CVI**  
200 is both progressive and irreversible, clinical symptoms associated with venous insufficiency increase in  
201 severity with time (Suzuki et al., 2009). Important efforts are still necessary to predict numerically the  
202 long-term action of MCS in preventing the progression of venous stasis and the apparition of associated  
203 symptoms such as oedema, pigmentation, and **ulcers on** the skin.

204

## 205 **Conclusion**

206 In this study, a FE model of a human leg with a varicose vein has been developed to compute the stress  
207 distribution in and around the vein wall and analyse the biomechanical response of varicose veins to  
208 external compression in terms of trans-mural pressures. Experimental data on the mechanical properties  
209 of healthy superficial veins and varicose veins being scarce in literature, ultrasound images of *in vivo*  
210 varicose veins have been acquired and analysed to extract the material constants of the vein wall and that  
211 of the fat, using Finite Element Model Updating.

212

213 The model (brings)provides a new insight on MCS mechanical action and its possible benefits. The results  
214 confirm the idea that MCS work towards reducing (the) trans-mural pressure and are effective in  
215 narrowing leg veins, which is important for the clinical consequences.

216

217 Future developments include a validation of the proposed approach and of its medical outcomes using  
218 clinical studies.

219

## 220 **Acknowledgement**

221 None

## 222 **Conflict of interest**

223 None

224

## 225 **References**

- 226 AFNOR, 1986. NF G30-102. Article de bonneterie - Détermination de la pression de contention.
- 227 Agu, O., Hamilton, G., Baker, D., 1999. Graduated compression stockings in the prevention of venous  
228 thromboembolism. *British Journal of Surgery* 86, 992–1004.
- 229 Avril, S., Bouten, L., Dubuis, L., Drapier, S., Pouget, J.-F., 2010. Mixed Experimental and Numerical Approach  
230 for Characterizing the Biomechanical Response of the Human Leg Under Elastic Compression. *Journal of*  
231 *Biomechanical Engineering* 132, 31006–31014.
- 232 Bergan, J.J., 2007. *The Vein Book*. Academic Press.
- 233 Best, A.J., Williams, S., Crozier, A., Bhatt, R., Gregg, P.J., Hui, A.C.W., 2000. Graded compression stockings in  
234 elective orthopaedic surgery. *J Bone Joint Surg Br* 82-B, 116–118.
- 235 Buhs, C.L., Bendick, P.J., Glover, J.L., 1999. The effect of graded compression elastic stockings on the lower  
236 leg venous system during daily activity. *Journal of Vascular Surgery* 30, 830–835.
- 237 Chuong, C.J., Fung, Y.C., 1986. On Residual Stresses in Arteries. *Journal of Biomechanical Engineering* 108,  
238 189–192.
- 239 Dai, X., Liu, R., Li, Y., Zhang, M., Kwok, Y., 2007. Computational Textile, in: *Studies in Computational*  
240 *Intelligence*. Springer Berlin / Heidelberg, pp. 301–309.
- 241 Downie, S.P., Raynor, S.M., Firmin, D.N., Wood, N.B., Thom, S.A., Hughes, A.D., Parker, K.H., Wolfe, J.H.N., Xu,  
242 X.Y., 2008. Effects of Elastic Compression Stockings on Wall Shear Stress in Deep and Superficial Veins of  
243 the Calf. *Am J Physiol Heart Circ Physiol* 294, H2112–H2120.
- 244 Dubuis, L., Avril, S., Debayle, J., Badel, P., 2012. Identification of the material parameters of soft tissues in  
245 the compressed leg. *Computer Methods in Biomechanics and Biomedical Engineering* 15, 3–11.
- 246 Flynn, C., Taberner, A., Nielsen, P., 2011. Mechanical characterisation of in vivo human skin using a 3D  
247 force-sensitive micro-robot and finite element analysis. *Biomechanics and Modeling in Mechanobiology*  
248 10, 27–38.
- 249 Gaied, I., Drapier, S., Lun, B., 2006. Experimental assessment and analytical 2D predictions of the stocking  
250 pressures induced on a model leg by Medical Compressive Stockings. *Journal of Biomechanics* 39, 3017–  
251 3025.
- 252 Gardon-Mollard, Ramel, 2008. *La compression médicale*. Elsevier Masson.
- 253 Gerhardt, L. -c, Lenz, A., Spencer, N.D., Münzer, T., Derler, S., 2009. Skin–textile friction and skin elasticity  
254 in young and aged persons. *Skin Research and Technology* 15, 288–298.
- 255 Guesdon, P., Fullana, J.-M., Flaud, P., 2007. Experimental study of muscular draining. *Comptes Rendus*  
256 *Mécanique* 335, 207–212.
- 257 Gusic, R.J., Petko, M., Myung, R., William Gaynor, J., Gooch, K.J., 2005. Mechanical properties of native and  
258 ex vivo remodeled porcine saphenous veins. *Journal of Biomechanics* 38, 1770–1779.
- 259 Hamel-Desnos, C.M., Guias, B.J., Desnos, P.R., Mesgard, A., 2010. Foam Sclerotherapy of the Saphenous  
260 Veins: Randomised Controlled Trial with or without Compression. *European Journal of Vascular and*  
261 *Endovascular Surgery* 39, 500–507.

- 262 Han, H.-C., 2007. A biomechanical model of artery buckling. *Journal of Biomechanics* 40, 3672–3678.
- 263 Han, H.-C., 2009. Blood vessel buckling within soft surrounding tissue generates tortuosity. *Journal of*  
264 *Biomechanics* 42, 2797–2801.
- 265 Han, H.-C., 2011. Determination of the Critical Buckling Pressure of Blood Vessels Using the Energy  
266 Approach. *Ann Biomed Eng* 39, 1032–1040.
- 267 Ibegbuna, V., Delis, K.T., Nicolaidis, A.N., Aina, O., 2003. Effect of elastic compression stockings on venous  
268 hemodynamics during walking. *Journal of Vascular Surgery* 37, 420–425.
- 269 Kamm, R.D., Shapiro, A.H., 1979. Unsteady Flow in a Collapsible Tube Subjected to External Pressure or  
270 Body Forces. *Journal of Fluid Mechanics* 95, 1–78.
- 271 Katz, A.I., Chen, Y., Moreno, A.H., 1969. Flow through a Collapsible Tube: Experimental Analysis and  
272 Mathematical Model. *Biophysical Journal* 9, 1261–1279.
- 273 Kern, P., Ramelet, A.-A., Wütschert, R., Hayoz, D., 2007. Compression after sclerotherapy for telangiectasias  
274 and reticular leg veins: A randomized controlled study. *Journal of Vascular Surgery* 45, 1212–1216.
- 275 Lee, A., Han, H.-C., 2010. A Nonlinear Thin-Wall Model for Vein Buckling. *Cardiovascular Engineering and*  
276 *Technology* 1, 282–289.
- 277 Liu, R., Kwok, Y.-L., Li, Y., Lao, T.-T., Zhang, X., Dai, X., 2006. A three-dimensional biomechanical model for  
278 numerical simulation of dynamic pressure functional performances of graduated compression stocking  
279 (GCS). *Fibers and Polymers* 7, 389–397.
- 280 Liu, R., Kwok, Y.L., Li, Y., Lao, T.T.H., Zhang, X., Dai, X.Q., 2005. Objective Evaluation of Skin Pressure  
281 Distribution of Graduated Elastic Compression Stockings. *Dermatologic Surgery* 31, 615–624.
- 282 Martinez, R., Fierro, C., Shireman, P., Han, H.-C., 2010. Mechanical Buckling of Veins Under Internal  
283 Pressure. *Annals of Biomedical Engineering* 38, 1345–1353.
- 284 Mayberry, J.C., Moneta, G.L., De Frang, R.D., Porter, J.M., 1991. The influence of elastic compression  
285 stockings on deep venous hemodynamics. *Journal of Vascular Surgery* 13, 91–100.
- 286 Moreno, A.H., Katz, A.I., Gold, L.D., Reddy, R.V., 1970. Mechanics of Distension of Dog Veins and Other Very  
287 Thin-Walled Tubular Structures. *Circulation Research* 27, 1069–1080.
- 288 Nehler, M.R., Moneta, G.L., Chitwood, R.W., Porter, J.M., 1992. The Lower Extremity Venous System Part III:  
289 Nonoperative Treatment of Chronic Venous Insufficiency. *PERSPECT VASC SURG ENDOVASC THER* 5,  
290 100–114.
- 291 Nehler, M.R., Moneta, G.L., Woodard, D.M., Defrang, R.D., Harker, C.T., Taylor Jr., L.M., Porter, J.M., 1993.  
292 Perimalleolar subcutaneous tissue pressure effects of elastic compression stockings. *Journal of Vascular*  
293 *Surgery* 18, 783–788.
- 294 Partsch, B., Partsch, H., 2005. Calf compression pressure required to achieve venous closure from supine  
295 to standing positions. *Journal of Vascular Surgery* 42, 734–738.
- 296 Partsch, H., 2007. Chapter 10 - Mechanism and effects of compression therapy, in: *The Vein Book*.  
297 Academic Press, Burlington, pp. 103–109.
- 298 Partsch, H., Mosti, G., Mosti, F., 2010. Narrowing of leg veins under compression demonstrated by  
299 magnetic resonance imaging (MRI). *Int Angiol* 29, 408–410.

300 Suzuki, M., Unno, N., Yamamoto, N., Nishiyama, M., Sagara, D., Tanaka, H., Mano, Y., Konno, H., 2009.  
301 Impaired lymphatic function recovered after great saphenous vein stripping in patients with varicose  
302 vein: Venodynamic and lymphodynamic results. *Journal of Vascular Surgery* 50, 1085–1091.

303 Travers, J.P., Brookes, C.E., Evans, J., Baker, D.M., Kent, C., Makin, G.S., Mayhew, T.M., 1996. Assessment of  
304 wall structure and composition of varicose veins with reference to collagen, elastin and smooth muscle  
305 content. *European Journal of Vascular and Endovascular Surgery* 11, 230–237.

306 Villavicencio, J., 2009. Sclerotherapy in the management of varicose veins of the extremities., in: *Handbook*  
307 *of Venous Disorders: Guidelines of the American Venous Forum*. Gloviczki, P. and Yao J., London, pp. 366–  
308 379.

309 Wang, Y., Pierce, I., Gatehouse, P., Wood, N., Firmin, D., Xu, X.Y., 2012. Analysis of flow and wall shear stress  
310 in the peroneal veins under external compression based on real-time MR images. *Medical Engineering &*  
311 *Physics* 34, 17–27.

312 Wells, P.N.T., Liang, H.-D., 2011. Medical Ultrasound: Imaging of Soft Tissue Strain and Elasticity. *J. R. Soc.*  
313 *Interface* 8, 1521–1549.

314 Wesly, R.L., Vaishnav, R.N., Fuchs, J.C., Patel, D.J., Greenfield, J.C., 1975. Static Linear and Nonlinear Elastic  
315 Properties of Normal and Arterialized Venous Tissue in Dog and Man. *Circulation Research* 37, 509–520.

316 Wildin, C.J., Hui, A.C.W., Esler, C.N.A., Gregg, P.J., 1998. In vivo pressure profiles of thigh-length graduated  
317 compression stockings. *British Journal of Surgery* 85, 1228–1231.

318 Yeung, K.W., Li, Y., Zhang, X., 2004. A 3D Biomechanical Human Model for Numerical Simulation of  
319 Garment–Body Dynamic Mechanical Interactions During Wear. *Journal of the Textile Institute* 95, 59–79.

320 Zhao, J., Jesper Andreasen, J., Yang, J., Steen Rasmussen, B., Liao, D., Gregersen, H., 2007. Manual pressure  
321 distension of the human saphenous vein changes its biomechanical properties—implication for coronary  
322 artery bypass grafting. *Journal of Biomechanics* 40, 2268–2276.

323

324

325

## List of figures

|          |  |
|----------|--|
| Figure 1 | Acquisition of Echographic images both in the standing and supine position (1a and 1b). A special precaution was taken as illustrated in figure 1c.  |
| Figure 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. |

326

327

## List of tables

|         |  |
|---------|--|
| Table 1 | Material properties of the different constitutive parts of the model |
| Table 2 | Default ABAQUS parameters used for the simulation (Hibbitt, 2009)    |

328

329

|          |   |
|----------|---|
| Table A1 | Influence of the ratio of adipose tissue to leg size. The thickness of the adipose tissue has been modified during the segmentation step to account for different morphologies of subcutaneous adipose tissue (Reference configuration and geometries 1, 2 and 3 hereunder). The results show that the amount of adipose tissue has a negligible influence both on the decrease in the vein cross-section and on the decrease in trans-mural pressure.  |
| Table A2 | Influence of the position of the vein on the leg contour. The vein is placed at different positions on the leg contour (Reference configuration and geometries 1, 2 and 3 hereunder). The maximum values of decrease in trans-mural pressure, percentage circumferential stretch ratio and increase in hydrostatic pressure in fat, are obtained when the radius of curvature is the smallest. These results confirm that the performance of the MCS is correlated to the local radius of curvature of the leg.   |
| Table A3 | Influence of the cross-sectional area of the vein. Different veins are generated from the segmented geometry of the vein in vivo by doing a dilation of the semi-minor and semi-major axes respectively. The centre of dilation is taken as the centre of the vein and the scaling factor as 0.7, 0.5 and 0.2 respectively (Reference configuration and geometries 1, 2 and 3 hereunder). The results show that MCS have a slightly more important effect as the cross section decreases, but overall the numerical values are very close. A more pronounced effect is obtained in the supine position. |
| Table A4 | Influence of the depth of the vein in the adipose tissue. New geometries are obtained by translating the vein in the direction of the skin or, on the contrary, closer to the muscular aponeurosis (Reference configuration and geometries 1, 2 and 3 hereunder). Almost no effect is obtained in the supine position. In the standing position, however, the benefit on the decrease in trans-mural pressure due to external compression, slightly but steadily increases (as) when the vein is closer to the skin.  |
| Table A5 | Influence of the external compression applied. The stiffness of the sock used in the reference model is multiplied by a constant of proportionality (i.e. 1, 2 and 3). The mean contact pressure delivered for each case is reported below. Results show a fine linear relationship between the mean contact pressure and the response of the leg. We observe moreover that the response is different in the standing and supine position, except for the mean increase in hydrostatic pressure in fat.   |
| Table A6 | Influence of the stiffness of the fat. Different “types” of fat are modelled by changing $C_{10}$ . The values are taken in the range 3-8 kPa $C_{10}$ . Results are reported hereunder. The main result is the significant influence of this parameter on the percentage compression of the vein in the supine position and the quasi-insignificant influence in the standing position.  |
| Table A7 | Influence of the compressibility of the fat. Different “types” of fat are modelled by changing $D_1$ . The values are taken in the range 0.005-10 MPa <sup>-1</sup> . Results are reported hereunder. Almost no effect is obtained either in the supine or standing positions.  |
| Table A8 | Influence of the constitutive behaviour law used to model the vein wall. Two types of behaviour laws were compared (i) bi-linear elastic and (ii) Neo-Hookean hyperelastic material model. Only weak differences are observed in the results.   |
| Table A9 | Influence of the element type used for the Finite Element mesh. Three aspects were considered (i) hybrid formulation of the elements (ii) reduced integration of these and (iii) geometric order (linear/quadratic). Results show that the choice of element formulation does not affect key conclusions of the study derived from the modelling  |



|           |   |
|-----------|---|
|           | results.  |
| Table A10 | Influence of the contact formulation for the <b>Fat/Vein</b> interface ( <b>Fat/Vein</b> ). Two aspects of the contact specifications were considered: (i) normal and (ii) tangential behaviour of the contact interaction properties. Both “hard” and “soft” constraint methods were investigated for enforcing the contact pressure-overclosure relationship (normal direction). Furthermore, a tie constraint (each node on the slave surface is constrained to have the same motion as the point on the master surface to which it is closest) was also investigated in place of the contact interaction. Results show minor changes. |
| Table A11 | Influence of the contact formulation for the <b>Fat/Muscle</b> interface ( <b>Fat/Muscle</b> ). The same contact conditions were investigated. Very little change was observed.   |
| Table A12 | Influence of the contact formulation for the <b>Skin/MCS</b> interface ( <b>Skin/MCS</b> ). Results show that the “softened” contact algorithms available in ABAQUS/Standard (and subsequently retained as a constraint method for enforcing the contact pressure-overclosure relationship) performed better than the “hard” contact algorithms. The main advantage of the “softened” contact algorithms is that clearance is calculated from surface to surface instead of from node to surface. As a consequence, the contact load is evenly distributed along the interacting surfaces.  |

332

333

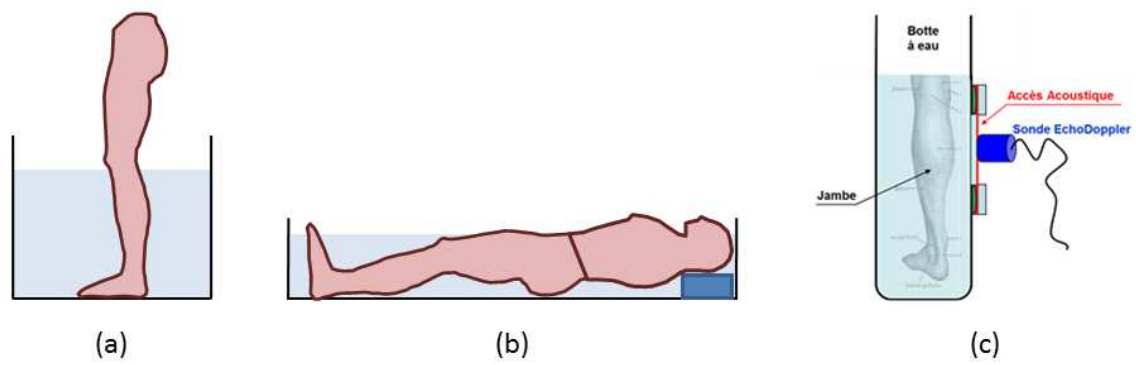


Figure 1. Acquisition of echographic images both in the standing and supine position (a and b). A special precaution was taken as illustrated in panel c.

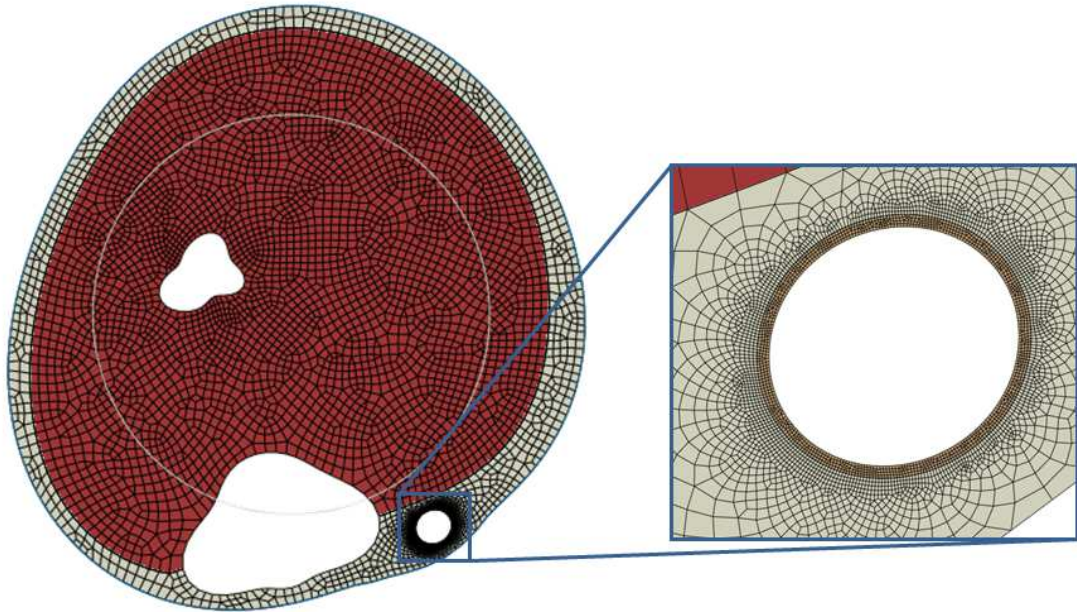



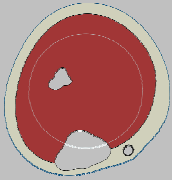
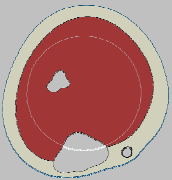
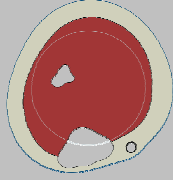
Figure 2: Finite element mesh of the 2D patient specific mesh. It consists of continuum plane strain elements for the muscle, fat and vein wall and truss elements for the muscular aponeurosis, skin and MCS. A relatively finer discretisation is used in the vicinity of the vein wall. The thickness-to-radius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

| Simulation element  | ABAQUS parameters used   |
|---|--|
| Truss elements  | Truss cross-sectional area = 1.0 mm <sup>2</sup>   |
| Contact pairs (for surfaces in contact)   | <i>Contact algorithm: pure master-slave contact</i>  |
| Contact between Skin and textile  | <p><b>Tangential Behaviour:</b><br/>Friction formulation=PENALTY,<br/>Behaviour independent of slip rate, pressure and temperature,<br/>friction coefficient = 0.3</p> <p><b>Normal Behaviour :</b><br/>Contact pressure-overclosure relationship= EXPONENTIAL (SOFT),<br/><i>This means that the contact pressure transmitted between the two interacting surfaces increases exponentially as the clearance between them, measured in the contact (normal) direction, diminishes (starting from a user-defined threshold value).</i><br/>Separation of the surfaces is not allowed<br/>Constraint Enforcement Method= PENALTY</p> |
| Contact fat-muscle  | <p><b>Tangential Behaviour : FRICTIONLESS</b></p> <p><b>Normal Behaviour:</b><br/>Contact pressure-overclosure relationship= EXPONENTIAL<br/>Separation of the surfaces is not allowed<br/>Constraint enforcement method= AUGMENTED_LAGRANGE</p>   |
| Constraint between surfaces :-<br>-1- Bone-Fat<br>-2- Bone-Muscle<br>-3- Fat-Vein<br>-4- Aponeurosis-Muscle<br>-5- Skin-Fat | <p>Type of constraint : TIE</p> <p><i>Tie constraint means that each node on the slave surface is constrained to have the same motion as the point on the master surface to which it is closest</i></p> <p>Slave surfaces are adjusted so that surfaces are in contact</p> <p>Rotational DOF are also tied</p>   |
| Steps of the FE analysis (steps 1 to 3)   | <p>Implicit resolution</p> <p>Maximum number of steps allowed = 100</p> <p>Initial increment time step size = 1.0s</p> <p>Minimum increment time step size = 1e-5s</p> <p>Maximum increment time step size = 1.0s</p> <p>Nlgeom=ON</p> <p>Solution technique = Full Newton</p> <p>Equation solver = Direct (<i>i.e. the solver finds the exact solution (up to machine precision) of the set of linear equations obtained at each iteration of the Newton method. It uses a sparse, direct, Gauss elimination method</i>)</p>  |

**Table 1: Default ABAQUS parameters used for the simulation (Hibbitt, 2009).**

| Material             | Model   | Material parameters   | Source  |
|----------------------|---|---|---|
| Fat                  | Hyper-elastic Neo-Hookean                                   | $C_{10} = 0.005 \text{ MPa}$<br>$D_1 = 0.14 \text{ MPa}^{-1}$ | Inverse identification (Dubuis et al., 2011) (Avril et al., 2010)                             |
| Muscle               | Hyper-elastic Neo-Hookean                                   | $C_{10} = 0.003 \text{ MPa}$<br>$D_1 = 0.14 \text{ MPa}^{-1}$ | (Dubuis et al., 2011) (Avril et al., 2010)  |
| Skin                 | Hyper-elastic Neo-Hookean                                   | $C_{10} = 0.1 \text{ MPa}$<br>$D_1 = 0.14 \text{ MPa}^{-1}$   | (Iivarinen et al., 2011) (Hendriks et al., 2006)  |
| Muscular aponeurosis | Hyper-elastic Neo-Hookean                                   | $C_{10} = 10 \text{ MPa}$<br>$D_1 = 80 \text{ MPa}^{-1}$      | (Wu, 2007)  |
| Vein wall            | Linearized (in standing and resting positions respectively) | $\nu = 0.49$ (fixed)  | Inverse identification  |
| MCS                  | Linear elastic  | $E = 0.39$<br>$\nu = 0.49$                                    | SIGVARIS tensile test on 15-20 mmHg MCS and based on the French norm NF-G30-102 (AFNOR, 1986) |

**Table 2: Material properties of the different constitutive parts of the model.**

| <b>Morphology of adipose tissue</b>                                 |   |      |          |       |   |      |          |       |   |      |          |       |   |      |          |       |
|---|---|------|----------|-------|---|------|----------|-------|---|------|----------|-------|---|------|----------|-------|
|   |  |      |          |       |  |      |          |       |  |      |          |       |  |      |          |       |
| <b>Note : all pressures given in mmHg</b>                           | Reference configuration   |      |          |       | Geometry1   |      |          |       | Geometry2   |      |          |       | Geometry3   |      |          |       |
|   | Supine  |      | Standing |       | Supine  |      | Standing |       | Supine  |      | Standing |       | Supine  |      | Standing |       |
| <b>Percentage circumferential reduction of the vein lumen</b>       | 10.0  |      | 3.2      |       | 10.1  |      | 3.3      |       | 10.2  |      | 3.3      |       | 10.3  |      | 3.3      |       |
| <b>Average contact pressure at skin-sock interface</b>              | 17.3  | ±5.3 | 17.4     | ±5.8  | 17.3  | ±5.4 | 17.3     | ±6.0  | 17.4  | ±5.8 | 17.4     | ±6.1  | 17.4  | ±5.5 | 17.4     | ±6.0  |
| <b>Mean trans-mural pressure in vein wall before EC</b>             | 11.0  | ±1.1 | 67.2     | ±5.4  | 11.0  | ±1.1 | 67.1     | ±5.5  | 11.0  | ±1.1 | 67.1     | ±5.7  | 11.0  | ±1.1 | 67.1     | ±6.0  |
| <b>Mean decrease of trans-mural pressure in vein wall due to EC</b> | 4.8   | ±2.5 | 12.3     | ±11.1 | 4.8   | ±2.7 | 12.2     | ±11.7 | 5.0   | ±2.5 | 12.6     | ±11.0 | 4.9   | ±2.6 | 12.5     | ±11.3 |
| <b>Mean increase in hydrostatic pressure in fat due to EC</b>       | 19.8  | ±3.7 | 19.9     | ±6.6  | 19.7  | ±3.7 | 19.5     | ±6.4  | 19.6  | ±3.6 | 19.8     | ±5.8  | 19.2  | ±3.5 | 19.5     | ±5.7  |
| <b>Maximum hydrostatic pressure in fat</b>                          | 29.0  |      | 39.3     |       | 32.8  |      | 44.0     |       | 41.2  |      | 43.8     |       | 29.9  |      | 39.3     |       |

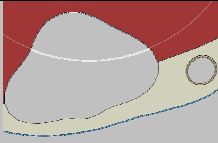
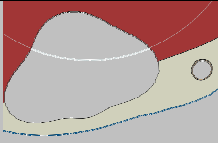
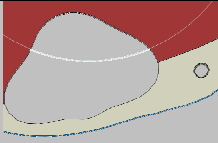
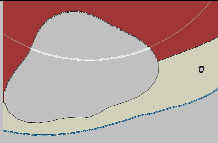
Note: average results given as *mean ± standard deviation*

Table A1: Ratio of adipose tissue to leg size

| Position of the vein on the leg contour                             | Reference configuration |            | Geometry1 |            | Geometry2 |            | Geometry3 |            |
|---|-------------------------|------------|-----------|------------|-----------|------------|-----------|------------|
|   | Supine                  | Standing   | Supine    | Standing   | Supine    | Standing   | Supine    | Standing   |
| <b>Note : all pressures given in mmHg</b>                           |                         |            |           |            |           |            |           |            |
| <b>Percentage circumferential reduction of the vein lumen</b>       | 10.0                    | 3.2        | 11.0      | 3.5        | 12.3      | 4.0        | 10.7      | 4.0        |
| <b>Average contact pressure at skin-sock interface</b>              | 17.3 ±5.3               | 17.4 ±5.8  | 17.3 ±5.4 | 17.3 ±6.0  | 17.4 ±5.8 | 17.4 ±6.1  | 17.5 ±5.5 | 17.4 ±6.1  |
| <b>Mean trans-mural pressure in vein wall before EC</b>             | 11.0 ±1.1               | 67.2 ±5.4  | 11.0 ±1.1 | 67.1 ±5.4  | 11.0 ±1.1 | 67.2 ±5.6  | 11.0 ±1.1 | 67.2 ±5.6  |
| <b>Mean decrease of trans-mural pressure in vein wall due to EC</b> | 4.8 ±2.5                | 12.3 ±11.1 | 5.3 ±2.1  | 13.2 ±11.2 | 6.0 ±3.5  | 14.9 ±12.0 | 5.1 ±2.9  | 14.9 ±12.0 |
| <b>Mean increase in hydrostatic pressure in fat due to EC</b>       | 19.8 ±3.7               | 19.9 ±6.6  | 21.4 ±4.8 | 20.6 ±7.0  | 23.1 ±5.9 | 22.2 ±7.1  | 21.1 ±4.7 | 22.2 ±7.1  |
| <b>Maximum hydrostatic pressure in fat</b>                          | 29.0                    | 39.3       | 48.0      | 48.0       | 42.9      | 54.9       | 42.7      | 54.9       |

Note: average results given as *mean ± standard deviation*

Table A2: Position on the leg contour

|  |  |      |  |       |  |      |  |      |        |      |          |      |        |      |          |      |
|--|---|------|--|-------|---|------|---|------|--------|------|----------|------|--------|------|----------|------|
| Initial vein c/s of vein lumen (in mm <sup>2</sup> )         | 21.9  |      | 11.2   |       | 5.9   |      | 1.0   |      |        |      |          |      |        |      |          |      |
| Note : all pressures given in mmHg                           | Reference configuration   |      | Geometry1  |       | Geometry2   |      | Geometry3   |      |        |      |          |      |        |      |          |      |
|  | Supine  |      | Standing   |       | Supine  |      | Standing  |      | Supine |      | Standing |      | Supine |      | Standing |      |
| Percentage circumferential reduction of the vein lumen       | 10.0  |      | 3.2  |       | 10.3  |      | 3.4   |      | 10.4   |      | 3.5      |      | 10.6   |      | 3.6      |      |
| Average contact pressure at skin-sock interface              | 17.3  | ±5.3 | 17.4   | ±5.8  | 17.3  | ±5.5 | 17.4  | ±5.7 | 17.3   | ±5.6 | 17.3     | ±5.8 | 17.3   | ±5.7 | 17.3     | ±5.7 |
| Mean trans-mural pressure in vein wall before EC             | 11.0  | ±1.1 | 67.2   | ±5.4  | 8.8   | ±0.7 | 63.5  | ±4.6 | 7.5    | ±0.6 | 61.2     | ±4.3 | 5.5    | ±0.4 | 57.6     | ±4.1 |
| Mean decrease of trans-mural pressure in vein wall due to EC | 4.8   | ±2.5 | 12.3   | ±11.1 | 5.3   | ±2.3 | 12.4  | ±9.7 | 5.6    | ±2.3 | 12.4     | ±8.9 | 5.9    | ±2.6 | 12.4     | ±8.5 |
| Mean increase in hydrostatic pressure in fat due to EC       | 19.8  | ±3.7 | 19.9   | ±6.6  | 20.5  | ±3.7 | 20.5  | ±5.6 | 20.6   | ±3.8 | 20.9     | ±5.2 | 20.8   | ±3.5 | 21.1     | ±4.0 |
| Maximum hydrostatic pressure in fat                          | 29.0  |      | 39.3   |       | 29.7  |      | 36.3  |      | 33.4   |      | 36.2     |      | 33.6   |      | 34.1     |      |

Note: average results given as *mean ± standard deviation*

Table A3: Vein lumen size





| <b>Mean external compression applied on skin (mmHg)</b>             | 17.4                    |          | 34.7            |          | 52.0            |          | 69.4            |          |      |       |      |       |       |       |       |       |
|---|-------------------------|----------|-----------------|----------|-----------------|----------|-----------------|----------|------|-------|------|-------|-------|-------|-------|-------|
| <b>Note : all pressures given in mmHg</b>                           | Reference configuration |          | Configuration 1 |          | Configuration 2 |          | Configuration 3 |          |      |       |      |       |       |       |       |       |
|   | Supine                  | Standing | Supine          | Standing | Supine          | Standing | Supine          | Standing |      |       |      |       |       |       |       |       |
| <b>Percentage circumferential reduction of the vein lumen</b>       | 10.0                    | 3.2      | 16.8            | 5.7      | 22.4            | 7.9      | 27.4            | 10.0     |      |       |      |       |       |       |       |       |
| <b>Average contact pressure at skin-sock interface</b>              | 17.3                    | ±5.3     | 17.4            | ±5.8     | 34.7            | ±9.3     | 34.7            | ±9.8     | 52.0 | ±12.9 | 52.0 | ±13.4 | 69.3  | ±16.6 | 69.4  | ±17.2 |
| <b>Mean trans-mural pressure in vein wall before EC</b>             | 11.0                    | ±1.1     | 67.2            | ±5.4     | 11.0            | ±1.1     | 67.2            | ±5.4     | 11.0 | ±1.1  | 67.2 | ±5.4  | 11.0  | ±1.1  | 67.2  | ±5.4  |
| <b>Mean decrease of trans-mural pressure in vein wall due to EC</b> | 4.8                     | ±2.5     | 12.3            | ±11.1    | 10.1            | ±4.5     | 23.7            | ±10.3    | 16.0 | ±8.3  | 34.8 | ±9.3  | 22.1  | ±14.4 | 45.8  | ±8.6  |
| <b>Mean increase in hydrostatic pressure in fat due to EC</b>       | 19.8                    | ±3.7     | 19.9            | ±6.6     | 37.2            | ±6.3     | 38.3            | ±7.7     | 54.3 | ±9.2  | 56.2 | ±8.6  | 71.2  | ±12.8 | 73.7  | ±9.7  |
| <b>Maximum hydrostatic pressure in fat</b>                          | 29.0                    |          | 39.3            |          | 57.6            |          | 59.8            |          | 91.0 |       | 91.1 |       | 123.7 |       | 119.9 |       |

Note: average results given as *mean ± standard deviation*

Table A5: Effect of the applied external compression

| <b>C<sub>10</sub> Fat (kPa)</b>                                     | 3               |      |          |       | 5                       |      |          |       | 6               |      |          |       | 7.5             |      |          |       |
|---|-----------------|------|----------|-------|-------------------------|------|----------|-------|-----------------|------|----------|-------|-----------------|------|----------|-------|
| <b>Note : all pressures given in mmHg</b>                           | Configuration 1 |      |          |       | Reference configuration |      |          |       | Configuration 2 |      |          |       | Configuration 3 |      |          |       |
|   | Supine          |      | Standing |       | Supine                  |      | Standing |       | Supine          |      | Standing |       | Supine          |      | Standing |       |
| <b>Percentage circumferential reduction of the vein lumen</b>       | 12.2            |      | 3.3      |       | 10.0                    |      | 3.2      |       | 9.2             |      | 3.1      |       | 8.3             |      | 3.0      |       |
| <b>Average contact pressure at skin-sock interface</b>              | 17.3            | ±4.9 | 28.7     | ±10.0 | 17.3                    | ±5.3 | 17.4     | ±5.8  | 17.4            | ±5.5 | 17.4     | ±5.9  | 17.4            | ±5.7 | 17.3     | ±6.2  |
| <b>Mean trans-mural pressure in vein wall before EC</b>             | 11.0            | ±1.1 | 67.3     | ±5.4  | 11.0                    | ±1.1 | 67.2     | ±5.4  | 11.0            | ±1.1 | 67.2     | ±5.4  | 11.0            | ±1.1 | 67.2     | ±5.4  |
| <b>Mean decrease of trans-mural pressure in vein wall due to EC</b> | 6.4             | ±2.4 | 12.9     | ±10.9 | 4.8                     | ±2.5 | 12.3     | ±11.1 | 4.3             | ±2.6 | 11.9     | ±11.1 | 3.7             | ±2.6 | 11.4     | ±11.2 |
| <b>Mean increase in hydrostatic pressure in fat due to EC</b>       | 18.7            | ±3.0 | 19.1     | ±5.9  | 19.8                    | ±3.7 | 19.9     | ±6.6  | 20.3            | ±4.1 | 20.2     | ±6.8  | 20.9            | ±4.7 | 20.5     | ±7.1  |
| <b>Maximum hydrostatic pressure in fat</b>                          | 27.6            |      | 36.1     |       | 29.0                    |      | 39.3     |       | 29.9            |      | 40.4     |       | 32.1            |      | 42.4     |       |

Note: average results given as *mean ± standard deviation*

Table A6: Influence of the “type” of fat for the stiffness

| <b>D<sub>1</sub> Fat (MPa<sup>-1</sup>)</b>                         | 0.005           |      |          |       | 0.14                    |      |          |       | 1               |      |          |       | 10              |      |          |       |
|---|-----------------|------|----------|-------|-------------------------|------|----------|-------|-----------------|------|----------|-------|-----------------|------|----------|-------|
| <b>Note : all pressures given in mmHg</b>                           | Configuration 1 |      |          |       | Reference configuration |      |          |       | Configuration 2 |      |          |       | Configuration 3 |      |          |       |
|   | Supine          |      | Standing |       | Supine                  |      | Standing |       | Supine          |      | Standing |       | Supine          |      | Standing |       |
| <b>Percentage circumferential reduction of the vein lumen</b>       | 10.0            |      | 3.2      |       | 10.0                    |      | 3.2      |       | 10.0            |      | 3.2      |       | 10.0            |      | 3.2      |       |
| <b>Average contact pressure at skin-sock interface</b>              | 17.4            | ±5.4 | 17.4     | ±5.9  | 17.3                    | ±5.3 | 17.4     | ±5.8  | 17.4            | ±5.4 | 17.3     | ±5.8  | 17.3            | ±5.3 | 17.3     | ±5.4  |
| <b>Mean trans-mural pressure in vein wall before EC</b>             | 11.0            | ±1.1 | 67.4     | ±5.4  | 11.0                    | ±1.1 | 67.2     | ±5.4  | 11.0            | ±1.1 | 67.2     | ±5.4  | 11.0            | ±1.1 | 67.2     | ±5.4  |
| <b>Mean decrease of trans-mural pressure in vein wall due to EC</b> | 4.8             | ±2.5 | 12.2     | ±11.1 | 4.8                     | ±2.5 | 12.3     | ±11.1 | 4.8             | ±2.5 | 12.3     | ±11.1 | 4.7             | ±2.7 | 12.0     | ±11.2 |
| <b>Mean increase in hydrostatic pressure in fat due to EC</b>       | 19.8            | ±3.8 | 19.9     | ±6.6  | 19.8                    | ±3.7 | 19.9     | ±6.6  | 19.6            | ±3.7 | 19.8     | ±6.6  | 18.4            | ±3.6 | 18.4     | ±6.1  |
| <b>Maximum hydrostatic pressure in fat</b>                          | 29.1            |      | 39.1     |       | 29.0                    |      | 39.3     |       | 28.5            |      | 38.9     |       | 26.4            |      | 36.1     |       |

Note: average results given as *mean ± standard deviation*

Table A7: Influence of the “type” of fat for the incompressibility parameter

| <b>Constitutive behaviour law for the vein wall</b>                 | Bi-linear elastic model |      |          |       | Neo-Hookean material behaviour law |      |          |       |
|---|-------------------------|------|----------|-------|------------------------------------|------|----------|-------|
| <b>Note : all pressures given in mmHg</b>                           | Reference configuration |      |          |       |                                    |      |          |       |
|   | Supine                  |      | Standing |       | Supine                             |      | Standing |       |
| <b>Percentage circumferential reduction of the vein lumen</b>       | 10.0                    |      | 3.2      |       | 9.8                                |      | 3.2      |       |
| <b>Average contact pressure at skin-sock interface</b>              | 17.3                    | ±5.3 | 17.4     | ±5.8  | 17.3                               | ±5.3 | 17.3     | ±5.8  |
| <b>Mean trans-mural pressure in vein wall before EC</b>             | 11.0                    | ±1.1 | 67.2     | ±5.4  | 11.0                               | ±1.3 | 67.1     | ±6.6  |
| <b>Mean decrease of trans-mural pressure in vein wall due to EC</b> | 4.8                     | ±2.5 | 12.3     | ±11.1 | 5.3                                | ±2.7 | 12.2     | ±12.4 |
| <b>Mean increase in hydrostatic pressure in fat due to EC</b>       | 19.8                    | ±3.7 | 19.9     | ±6.6  | 19.8                               | ±3.7 | 19.9     | ±6.5  |
| <b>Maximum hydrostatic pressure in fat</b>                          | 29.0                    |      | 39.3     |       | 29.0                               |      | 39.2     |       |

Note: average results given as *mean ± standard deviation*

Table 8A:

| Element type used for the FE mesh                                   | Normal formulation (CPE4, CPE3, T2D2) |      |          |       | Reduced integration (CPE4R, CPE3, T2D2) |      |          |       | Hybrid formulation and reduced integration (CPE4RH, CPE3H, T2D2H) |      |          |       | Geometric order: Quadratic elements used instead of linear elements (CPE8, CPE6, T2D3) |       |          |       |
|---|---------------------------------------|------|----------|-------|---|------|----------|-------|---|------|----------|-------|--|-------|----------|-------|
|   | Reference configuration               |      |          |       |   |      |          |       |   |      |          |       |  |       |          |       |
|   | Supine                                |      | Standing |       | Supine                                  |      | Standing |       | Supine  |      | Standing |       | Supine   |       | Standing |       |
| <b>Percentage circumferential reduction of the vein lumen</b>       | 10.0                                  |      | 3.2      |       | 10.0                                    |      | 3.2      |       | 10.0  |      | 3.2      |       | 10.0   |       | 3.2      |       |
| <b>Average contact pressure at skin-sock interface</b>              | 17.3                                  | ±5.3 | 17.3     | ±5.8  | 17.3                                    | ±5.3 | 17.3     | ±5.8  | 17.3  | ±5.3 | 17.4     | ±5.8  | 17.6   | ±6.0  | 17.6     | ±6.4  |
| <b>Mean trans-mural pressure in vein wall before EC</b>             | 10.9                                  | ±1.1 | 67.1     | ±5.8  | 11.0                                    | ±1.1 | 67.2     | ±5.4  | 11.0  | ±1.1 | 67.2     | ±5.4  | 14.5   | ±1.2  | 88.3     | ±6.7  |
| <b>Mean decrease of trans-mural pressure in vein wall due to EC</b> | 5.9                                   | ±2.7 | 14.8     | ±13.1 | 4.8                                     | ±2.5 | 12.3     | ±11.1 | 4.8   | ±2.5 | 12.3     | ±11.1 | 6.3  | ±3.1  | 16.1     | ±13.0 |
| <b>Mean increase in hydrostatic pressure in fat due to EC</b>       | 19.8                                  | ±3.8 | 19.9     | ±6.6  | 19.8                                    | ±3.7 | 19.9     | ±6.6  | 19.8  | ±3.7 | 19.9     | ±6.6  | 20.6   | ±16.6 | 20.4     | ±17.6 |
| <b>Maximum hydrostatic pressure in fat</b>                          | 29.2                                  |      | 39.6     |       | 29.1                                    |      | 39.2     |       | 29.0  |      | 39.3     |       | 286.0  |       | 285.7    |       |

Note: average results given as *mean ± standard deviation*

Table A9

| Contact formulation for the interface Fat/Vein                      | Tie constraint          |      |          |       | Frictionless |      |          |       | Friction - "Hard" contact contact pressure-overclosure relationship |      |          |       | Friction - Exponential ("Soft") contact pressure-overclosure relationship |      |          |       |
|---|-------------------------|------|----------|-------|--------------|------|----------|-------|---|------|----------|-------|---|------|----------|-------|
|   | Reference configuration |      |          |       |              |      |          |       |   |      |          |       |   |      |          |       |
|   | Supine                  |      | Standing |       | Supine       |      | Standing |       | Supine  |      | Standing |       | Supine  |      | Standing |       |
| <b>Percentage circumferential reduction of the vein lumen</b>       | 9.9                     |      | 3.1      |       | 10.1         |      | 3.2      |       | 10.1  |      | 3.1      |       | 10.1  |      | 3.2      |       |
| <b>Average contact pressure at skin-sock interface</b>              | 17.3                    | ±5.3 | 17.4     | ±5.8  | 17.3         | ±5.3 | 17.4     | ±5.8  | 17.3  | ±5.3 | 17.4     | ±5.8  | 17.3  | ±5.3 | 17.4     | ±5.8  |
| <b>Mean trans-mural pressure in vein wall before EC</b>             | 11.0                    | ±1.1 | 67.2     | ±5.4  | 10.8         | ±1.1 | 67.2     | ±5.4  | 10.9  | ±1.1 | 67.2     | ±5.4  | 9.8   | ±0.9 | 64.6     | ±5.1  |
| <b>Mean decrease of trans-mural pressure in vein wall due to EC</b> | 4.7                     | ±2.5 | 12.0     | ±11.0 | 5.2          | ±2.3 | 12.8     | ±12.0 | 5.1   | ±1.9 | 12.4     | ±11.3 | 5.6   | ±1.6 | 12.7     | ±10.6 |
| <b>Mean increase in hydrostatic pressure in fat due to EC</b>       | 19.5                    | ±3.7 | 19.7     | ±6.5  | 19.9         | ±4.8 | 20.0     | ±4.9  | 19.8  | ±4.5 | 19.8     | ±5.5  | 20.0  | ±4.6 | 20.1     | ±5.6  |
| <b>Maximum hydrostatic pressure in fat</b>                          | 36.5                    |      | 39.4     |       | 35.2         |      | 35.6     |       | 34.9  |      | 37.0     |       | 29.8  |      | 38.0     |       |

Note: average results given as *mean ± standard deviation*

Table A10

| Contact formulation for the interface Fat/Muscle                    | Tie constraint |      |          |       | Frictionless |      |          |       | Friction - "Hard" contact contact pressure-overclosure relationship |      |          |       | Friction - Exponential ("Soft") contact pressure-overclosure relationship |      |          |       |
|---|----------------|------|----------|-------|--------------|------|----------|-------|---|------|----------|-------|---|------|----------|-------|
|   | Supine         |      | Standing |       | Supine       |      | Standing |       | Supine  |      | Standing |       | Supine  |      | Standing |       |
| <b>Note : all pressures given in mmHg</b>                           |                |      |          |       |              |      |          |       |   |      |          |       | Reference configuration   |      |          |       |
| <b>Percentage circumferential reduction of the vein lumen</b>       | 9.9            |      | 3.2      |       | 10.0         |      | 3.0      |       | 9.9   |      | 3.1      |       | 10.0  |      | 3.2      |       |
| <b>Average contact pressure at skin-sock interface</b>              | 17.3           | ±5.3 | 17.4     | ±5.8  | 17.3         | ±5.3 | 17.4     | ±5.8  | 17.3  | ±5.3 | 17.4     | ±5.8  | 17.3  | ±5.3 | 17.4     | ±5.8  |
| <b>Mean trans-mural pressure in vein wall before EC</b>             | 11.0           | ±1.1 | 67.3     | ±5.4  | 11.0         | ±1.1 | 67.2     | ±5.4  | 11.0  | ±1.1 | 67.2     | ±5.4  | 11.0  | ±1.1 | 67.2     | ±5.4  |
| <b>Mean decrease of trans-mural pressure in vein wall due to EC</b> | 4.8            | ±2.5 | 12.3     | ±11.1 | 4.6          | ±2.6 | 11.1     | ±11.2 | 4.7   | ±2.5 | 12.0     | ±11.0 | 4.8   | ±2.5 | 12.3     | ±11.1 |
| <b>Mean increase in hydrostatic pressure in fat due to EC</b>       | 19.6           | ±4.3 | 20.0     | ±7.0  | 19.4         | ±3.6 | 18.7     | ±6.4  | 19.5  | ±3.7 | 19.7     | ±6.5  | 19.8  | ±3.7 | 19.9     | ±6.6  |
| <b>Maximum hydrostatic pressure in fat</b>                          | 39.7           |      | 39.5     |       | 31.8         |      | 38.8     |       | 36.5  |      | 39.4     |       | 29.0  |      | 39.3     |       |

Note: average results given as *mean ± standard deviation*

Table A11



| Contact formulation for the interface Skin/MCS                      | Tie constraint   |          | Frictionless |            | Friction - "Hard" contact contact pressure-overclosure relationship |            |           |            | Friction - Exponential ("Soft") contact pressure-overclosure relationship |                         |  |  |  |
|---|--|----------|--------------|------------|---|------------|-----------|------------|---|-------------------------|--|--|--|
|   | Supine   | Standing | Supine       | Standing   | Supine  | Standing   | Supine    | Standing   | Supine  | Standing                |  |  |  |
| <b>Note : all pressures given in mmHg</b>                           |  |          |              |            |   |            |           |            |   | Reference configuration |  |  |  |
| <b>Percentage circumferential reduction of the vein lumen</b>       |  |          | 10.0         | 3.0        | 9.9   | 3.1        | 10.0      | 3.2        |   |                         |  |  |  |
| <b>Average contact pressure at skin-sock interface</b>              |  |          | 17.3 ±5.3    | 17.4 ±5.8  | 18.8 ±23.3  | 18.8 ±23.5 | 17.3 ±5.3 | 17.4 ±5.8  |   |                         |  |  |  |
| <b>Mean trans-mural pressure in vein wall before EC</b>             | Not relevant because loading of the leg is done by simulating the contact between the MCS and the skin |          | 11.0 ±1.1    | 67.2 ±5.4  | 11.0 ±1.1   | 67.2 ±5.4  | 11.0 ±1.1 | 67.2 ±5.4  |   |                         |  |  |  |
| <b>Mean decrease of trans-mural pressure in vein wall due to EC</b> |  |          | 4.6 ±2.6     | 11.1 ±11.2 | 4.7 ±2.5  | 12.0 ±11.0 | 4.8 ±2.5  | 12.3 ±11.1 |   |                         |  |  |  |
| <b>Mean increase in hydrostatic pressure in fat due to EC</b>       |  |          | 19.4 ±3.6    | 18.7 ±6.4  | 19.5 ±3.7   | 19.7 ±6.5  | 19.8 ±3.7 | 19.9 ±6.6  |   |                         |  |  |  |
| <b>Maximum hydrostatic pressure in fat</b>                          |  |          | 31.8         | 38.8       | 36.5  | 39.4       | 29.0      | 39.3       |   |                         |  |  |  |

Note: average results given as *mean ± standard deviation*

Table A12