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A finite element implementation of a growth and remodeling model for soft biological tissues: verification and application to abdominal aortic aneurysms. (English) Zbl 1441.74127

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Summary: The general framework for growth and remodeling (G&R) of soft biological tissues shows a great potential for expanding our current understanding of biochemical and biomechanical processes, and to predict disease progression. Yet, its use is held up by the lack of a reliable and verified 3D finite element (FE) implementation capable of describing G&R processes of soft biological tissues. Thus, in this study we present the implementation of a 3D constrained mixture G&R model in a FE analysis program. In contrast to traditional finite strain FE formulations, we show that the volumetric-isochoric decomposition not only introduces numerical problems and instabilities, it also provides unphysical results. As a verification of the implementation we present adaptations of realistic aorta models to changes in the hemodynamics, i.e. changes in blood flow and pressure. The obtained results show a correspondence with the membrane theory and with clinical expectations. Application to a fusiform aneurysm model provided realistic growth rates, evolution of thickness and stress, whereas changes in the kinetic parameters show good agreement to animal models. Finally, we present simulated expansions of an asymmetric fusiform aneurysm. Non-axisymmetric elastin degradation increased the curvature of the aorta, which is characteristic for abdominal aortic aneurysms.

MSC:

74L15 Biomechanical solid mechanics

74S05 Finite element methods applied to problems in solid mechanics

65M60 Finite element, Rayleigh-Ritz and Galerkin methods for initial value and initial-boundary value problems involving PDEs

Keywords:

finite elements; vascular adaptation; collagen turnover; fusiform aneurysm; asymmetric fusiform aneurysm; growth and remodeling

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References:

[1] Humphrey, J. D.; Rajagopal, K. R., A constrained mixture model for growth and remodelling of soft tissues, Math. Model. Methods Appl. Sci., 12, 407-430 (2002) · Zbl 1021.74026

[2] Akintunde, A. R.; Miller, K. S., Evaluation of microstructurally motivated constitutive models to describe age-dependent tendon healing, Biomech. Model. Mechanobiol., 17, 793-814 (2018)

[3] Witzenburg, C. M.; Holmes, J. W., A comparison of phenomenologic growth laws for myocardial hypertrophy, J. Elasticity, 129, 257-281 (2017) · Zbl 1373.74026

[4] Wan, W.; Hansen, L.; Gleason, R. L., A 3-d constrained mixture model for mechanically mediated vascular growth and remodeling, Biomech. Model. Mechanobiol., 9, 403-419 (2010)

[5] Karšaj, I.; Sorić, J.; Humphrey, J. D., A 3-D framework for arterial growth and remodeling in response to altered hemodynamics, Internat. J. Engrg. Sci., 48, 1357-1372 (2011) · Zbl 1231.76369

[6] Karšaj, I.; Humphrey, J. D., A multilayered wall model of arterial growth and remodeling, Mech. Mater., 44, 110-119 (2012)

[7] Valentín, A.; Humphrey, J. D.; Holzapfel, G. A., A multi-layered computational model of coupled elastin degradation, vasoactive dysfunction, and collagenous stiffening in aortic aging, Ann. Biomed. Eng., 39, 2027-2045 (2011)

[8] Wilson, J. S.; Baek, S.; Humphrey, J. D., Importance of initial aortic properties on the evolving regional anisotropy, stiffness and wall thickness of human abdominal aortic aneurysms, J. R. Soc. Interface, 9, 2047-2058 (2012)

[9] Virag, L.; Wilson, J. S.; Humphrey, J. D.; Karšaj, I., Potential biomechanical roles of risk factors in the evolution of thrombus-laden abdominal aortic aneurysms, Int. J. Numer. Method. Biomed. Eng., 33, Article e2893 pp. (2017)

[10] Cyron, C. J.; Aydin, R. C.; Humphrey, J. D., A homogenized constrained mixture (and mechanical analog) model for growth and remodeling of soft tissue, Biomech. Model. Mechanobiol., 15, 1389-1403 (2016)

[11] Grytsan, A.; Eriksson, T. S.E.; Watton, P. N.; Gasser, T. C., Growth description for vessel wall adaptation: A thick-walled mixture model of abdominal aortic aneurysm evolution, Materials (Basel)., 10, Article e994 pp. (2017)

[12] Lin, W. J.; Iafrati, M. D.; Peattie, R. A.; Dorfmann, L., Growth and remodeling with application to abdominal aortic aneurysms, J. Eng. Math., 109, 113-137 (2017) · Zbl 1408.74038

[13] Baek, S.; Rajagopal, K. R.; Humphrey, J. D., A theoretical model of enlarging intracranial fusiform aneurysms, J. Biomech. Eng., 128, 142-149 (2006)

[14] Zeinali-Davarani, S.; Sheidaei, A.; Baek, S., A finite element model of stress-mediated vascular adaptation: Application to abdominal aortic aneurysms, Comput. Methods Biomech. Biomed. Eng., 14, 803-817 (2011)

[15] Wilson, J. S.; Baek, S.; Humphrey, J. D., Parametric study of effects of collagen turnover on the natural history of abdominal aortic aneurysms, Proc. R. Soc. A Math. Phys. Eng. Sci., 469, Article 20120556 pp. (2012) · Zbl 1371.92069

[16] Wu, J.; Shadden, S. C., Coupled simulation of hemodynamics and vascular growth and remodeling in a subject-specific geometry, Ann. Biomed. Eng., 43, 1543-1554 (2015)

[17] Tong, J.; Cohnert, T.; Regitnig, P.; Kohlbacher, J.; Birner-Gruenberger, R.; Schriefl, A. J., Variations of dissection properties and mass fractions with thrombus age in human abdominal aortic aneurysms, J. Biomech., 47, 14-23 (2014)

[18] Valentín, A.; Humphrey, J. D.; Holzapfel, G. A., A finite element-based constrained mixture implementation for arterial growth, remodeling, and adaptation: Theory and numerical verification, Int. J. Numer. Methods Biomed. Eng., 29, 822-849 (2013)

[19] Braeu, F. A.; Seitz, A.; Aydin, R. C.; Cyron, C. J., Homogenized constrained mixture models for anisotropic volumetric growth and remodeling, Biomech. Model. Mechanobiol., 16, 889-906 (2017)

[20] Valentin, A.; Cardamone, L.; Baek, S.; Humphrey, J. D., Complementary vasoactivity and matrix remodelling in arterial adaptations to altered flow and pressure, J. R. Soc. Interface, 6, 293-306 (2009)

[21] Sansour, C., On the physical assumptions underlying the volumetric-isochoric split and the case of anisotropy, Eur. J. Mech. A/Solids, 27, 28-39 (2008) · Zbl 1129.74009

[22] Federico, S., Volumetric-distortional decomposition of deformation and elasticity tensor, Math. Mech. Solids, 15, 672-690 (2009) · Zbl 1257.74018

[23] Helfenstein, J.; Jabareen, M.; Mazza, E.; Govindjee, S., On non-physical response in models for fiber-reinforced hyperelastic materials, Int. J. Solids Struct., 47, 2056-2061 (2010) · Zbl 1194.74042

[24] Gültekin, O.; Dal, H.; Holzapfel, G. A., On the quasi-incompressible finite element analysis of anisotropic hyperelastic materials, Comput. Mech., 63, 443-453 (2019) · Zbl 07037449

[25] Milewicz, D. M.; Guo, D.-C.; Tran-Fadulu, V.; Lafont, A. L.; Papke, C. L.; Inamoto, S., Genetic basis of thoracic aortic aneurysms and dissections: focus on smooth muscle cell contractile dysfunction, Annu. Rev. Genomics Hum. Genet., 9, 283-302 (2008)

[26] Walmsley, J. G.; Campling, M. R.; Chertkow, H. C., Interrelationship among wall structure, smooth muscle orientation, and contraction in human major cerebral arteries, Stroke., 14, 781-790 (1983)

[27] Länne, T.; Sonesson, B.; Bergqvist, D.; Bengtsson, H.; Gustafsson, D., Diameter and compliance in the male human abdominal aorta: influence of age and aortic aneurysm, Eur. J. Vasc. Surg., 6, 178-184 (1992)

[28] Valentin, A.; Humphrey, J. D., Evaluation of fundamental hypotheses underlying constrained mixture models of arterial growth and remodelling, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., 367, 3585-3606 (2009) · Zbl 1185.74069

[29] Valentín, A.; Humphrey, J. D., Parameter sensitivity study of a constrained mixture model of arterial growth and remodeling, J. Biomech. Eng., 131, Article 101006 pp. (2009)

[30] Karšaj, I.; Sorić, J.; Humphrey, J. D., A 3-d framework for arterial growth and remodeling in response to altered hemodynamics, Internat. J. Engrg. Sci., 48, 1357-1372 (2010) · Zbl 1231.76369

[31] Niestrawska, J. A.; Viertler, C.; Regitnig, P.; Cohnert, T. U.; Sommer, G.; Holzapfel, G. A., Microstructure and mechanics of healthy and aneurysmatic abdominal aortas: experimental analysis and modelling, J. R. Soc. Interface, 13, Article 20160620 pp. (2016)

[32] Brownlee, R. D.; Langille, B. L., Arterial adaptations to altered blood flow, Can. J. Physiol. Pharmacol., 69, 978-983 (1991)

[33] Schmidt-Trucksäss, A.; Schmid, A.; Brunner, C.; Scherer, N.; Zäch, G.; Keul, J., Arterial properties of the carotid and femoral artery in endurance-trained and paraplegic subjects, J. Appl. Physiol., 89, 1956-1963 (2000)

[34] Fridez, P.; Zulliger, M.; Bobard, F.; Montorzi, G.; Miyazaki, H.; Hayashi, K., Geometrical, functional, and histomorphometric adaptation of rat carotid artery in induced hypertension, J. Biomech., 36, 671-680 (2003)

[35] Hu, J. J.; Fossum, T. W.; Miller, M. W.; Xu, H.; Liu, J. C.; Humphrey, J. D., Biomechanics of the porcine basilar artery in hypertension, Ann. Biomed. Eng., 35, 19-29 (2007)

[36] Ntsinjana, H. N.; Biglino, G.; Capelli, C.; Tann, O.; Giardini, A.; Derrick, G., Aortic arch shape is not associated with hypertensive response to exercise in patients with repaired congenital heart diseases, J. Cardiovasc. Magn. Reson., 15, 101 (2013)

[37] Craiem, D.; Chironi, G.; Casciaro, M. E.; Redheuil, A.; Mousseaux, E.; Simon, A., Three-dimensional evaluation of thoracic aorta enlargement and unfolding in hypertensive men using non-contrast computed tomography, J. Hum. Hypertens., 27, 504-509 (2013)

[38] Martufi, G.; Satriano, A.; Moore, R. D.; Vorp, D. A.; Di Martino, E. S., Local quantification of wall thickness and intraluminal thrombus offer insight into the mechanical properties of the aneurysmal aorta, Ann. Biomed. Eng., 43, 1759-1771 (2015)

[39] Li, Z. Y.; Sadat, U.; U.-K.ing-Im, J.; Tang, T. Y.; Bowden, D. J.; Hayes, P. D., Association between aneurysm shoulder stress

and abdominal aortic aneurysm expansion: A longitudinal follow-up study, Circulation., 122, 1815-1822 (2010)

[40] Fillinger, M. F.; Marra, S. P.; Raghavan, M. L.; Kennedy, F. E., Prediction of rupture risk in abdominal aortic aneurysm during observation: Wall stress versus diameter, J. Vasc. Surg., 37, 724-732 (2003)

[41] Franck, G.; Dai, J.; Fifre, A.; Ngo, S.; Justine, C.; Michineau, S., Reestablishment of the endothelial lining by endothelial cell therapy stabilizes experimental abdominal aortic aneurysms, Circulation., 127, 1877-1887 (2013)

[42] Vande Geest, J. P.; Sacks, M. S.; Vorp, D. A., The effects of aneurysm on the biaxial mechanical behavior of human abdominal aorta, J. Biomech., 39, 1324-1334 (2006)

[43] Tong, J.; Cohnert, T.; Regitnig, P.; Holzapfel, G. A., Effects of age on the elastic properties of the intraluminal thrombus and the thrombus-covered wall in abdominal aortic aneurysms: Biaxial extension behaviour and material modelling, Eur. J. Vasc. Endovasc. Surg., 42, 207-219 (2011)

[44] Virag, L.; Wilson, J. S.; Humphrey, J. D.; Karšaj, I., A computational model of biochemomechanical effects of intraluminal thrombus on the enlargement of abdominal aortic aneurysms, Ann. Biomed. Eng., 43, 2852-2867 (2015)

[45] Federico, S., Volumetric-distortional decomposition of deformation and elasticity tensor, Math. Mech. Solids., 15, 672-690 (2009) · Zbl 1257.74018

[46] Baek, S.; Valentín, A.; Humphrey, J. D., Biochemomechanics of cerebral vasospasm and its resolution: II. Constitutive relations and model simulations, Ann. Biomed. Eng., 35, 1498-1509 (2007)

[47] Holzapfel, G. A.; Gasser, T. C.; Ogden, R. W., A new constitutive framework for arterial wall mechanics and a comparative study of material models, J. Elasticity, 61, 1-48 (2000) · Zbl 1023.74033