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The generalized Hill model: a kinematic approach towards active muscle contraction. (English) Zbl 1328.74063

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Summary: Excitation-contraction coupling is the physiological process of converting an electrical stimulus into a mechanical response. In muscle, the electrical stimulus is an action potential and the mechanical response is active contraction. The classical Hill model characterizes muscle contraction though one contractile element, activated by electrical excitation, and two non-linear springs, one in series and one in parallel. This rheology translates into an additive decomposition of the total stress into a passive and an active part. Here we supplement this additive decomposition of the stress by a multiplicative decomposition of the deformation gradient into a passive and an active part. We generalize the one-dimensional Hill model to the three-dimensional setting and constitutively define the passive stress as a function of the total deformation gradient and the active stress as a function of both the total deformation gradient and its active part. We show that this novel approach combines the features of both the classical stress-based Hill model and the recent active-strain models. While the notion of active stress is rather phenomenological in nature, active strain is micro-structurally motivated, physically measurable, and straightforward to calibrate. We demonstrate that our model is capable of simulating excitation-contraction coupling in cardiac muscle with its characteristic features of wall thickening, apical lift, and ventricular torsion.

MSC:

74L15 Biomechanical solid mechanics
92C10 Biomechanics
74F15 Electromagnetic effects in solid mechanics
74S05 Finite element methods applied to problems in solid mechanics

Keywords:

coupled cardiac electromechanics; excitation-contraction; active-strain; finite elements; Hill model

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References:

[1] Aliev, R. R.; Panfilov, A. V., A simple two-variable model of cardiac excitation, Chaos, Solitons and Fractals, 7, 293-301, (1996)

[2] Ambrosi, D.; Arioli, G.; Nobile, F.; Quarteroni, A., Electromechanical coupling in cardiac dynamicsthe active strain approach, SIAM J. Appl. Math., 71, 605-621, (2011) · Zbl 1419.74174

[3] Ambrosi, D.; Pezzuto, S., Active stress vs. active strain in mechanobiologyconstitutive issues, J. Elast., 107, 199-212, (2011) · Zbl 1312.74015

[4] Ask, A.; Menzel, A.; Ristinmaa, M., Electrostriction in electro-viscoelastic polymers, Mech. Mater., 50, 9-21, (2012)

[5] Ask, A.; Menzel, A.; Ristinmaa, M., Phenomenological modeling of viscous electrostrictive polymers, Int. J. Non-Linear Mech., 47, 156-165, (2012)

[6] Beeler, G. W.; Reuter, H., Reconstruction of the action potential of ventricular myocardial fibres, J. Physiol., 268, 177-210, (1977)

[7] Bers, D. M., Cardiac excitation-contraction coupling, Nature, 415, 198-205, (2002)

[8] Cherubini, C.; Filippi, S.; Nardinocchi, P.; Teresi, L., An electromechanical model of cardiac tissueconstitutive issues and electrophysiological effects, Prog. Biophys. Mol. Biol., 97, 562-573, (2008)

[9] Clayton, R. H.; Panfilov, A. V., A guide to modelling cardiac electrical activity in anatomically detailed ventricles, Prog. Biophys. Mol. Biol., 96, 19-43, (2008)

[10] Dal, H.; Göktepe, S.; Kaliske, M.; Kuhl, E., A fully implicit finite element method for bidomain models of cardiac electrophysiology, Comput. Methods Biomech. Biomed. Eng., 15, 645-656, (2012)

[11] Dal, H.; Göktepe, S.; Kaliske, M.; Kuhl, E., A fully implicit finite element method for bidomain models of cardiac electromechanics, Comput. Methods Appl. Mech. Eng., 253, 323-336, (2013) · Zbl 1297.74077

[12] Dokos, S.; Smaill, B. H.; Young, A. A.; LeGrice, I. J., Shear properties of passive ventricular myocardium, Am. J. Physiol.—Heart Circ. Physiol., 283, H2650-H2659, (2002)

[13] Doyle, T. C.; Ericksen, J. L., Nonlinear elasticity, (Dryden, H. L.; von Kármán, T., Advances in Applied Mechanics, vol. 4, (1956), Academic Press New York), 53-116

[14] Eriksson, T. S.E.; Prassl, A. J.; Plank, G.; Holzapfel, G. A., Influence of myocardial fiber/sheet orientations on left ventricular mechanical contraction, Math. Mech. Solids., 18, 592-606, (2013)

[15] Eriksson, T. S.E.; Prassl, A. J.; Plank, G.; Holzapfel, G. A., Modeling the dispersion in electromechanically coupled myocardium, Int. J. Numer. Methods Biomed. Eng., 29, 1267-1284, (2013)

[16] Fitzhugh, R., Impulses and physiological states in theoretical models of nerve induction, Biophys. J., 1, 455-466, (1961)

[17] Göktepe, S., 2014. Fitzhugh-Nagumo equation. In: Engquist, B. (Ed.), Encyclopedia of Applied and Computational Mathematics. Springer, in press.

[18] Göktepe, S.; Acharya, S. N.S.; Wong, J.; Kuhl, E., Computational modeling of passive myocardium, Int. J. Numer. Methods Biomed. Eng., 27, 1-12, (2011) · Zbl 1207.92006

[19] Göktepe, S.; Kuhl, E., Computational modeling of cardiac electrophysiologya novel finite element approach, Int. J. Numer. Methods Eng., 79, 156-178, (2009) · Zbl 1171.92310

[20] Göktepe, S.; Kuhl, E., Electromechanics of the hearta unified approach to the strongly coupled excitation-contraction problem, Comput. Mech., 45, 227-243, (2010) · Zbl 1183.78031

[21] Göktepe, S.; Menzel, A.; Kuhl, E., Micro-structurally based kinematic approaches to electromechanics of the heart, (Holzapfel, G. A.; Kuhl, E., Computer Models in Biomechanics, From Nano to Macro, (2013), Springer Science Business Media Dordrecht), 175-187, (chapter 13)

[22] Göktepe, S.; Wong, J.; Kuhl, E., Atrial and ventricular fibrillationcomputational simulation of spiral waves in cardiac tissue, Arch. Appl. Mech., 80, 569-580, (2010) · Zbl 1271.74319

[23] Hill, A. V., The heat of shortening and the dynamic constants of muscle, Proc. R. Soc. Lond. Ser. B—Biol. Sci., 126, 136-195, (1938)

[24] Hill, A. V., First and last experiments in muscle mechanics, (1970), Cambridge University Press London, New York

[25] Hodgkin, A.; Huxley, A., A quantitative description of membrane current and its application to excitation and conduction in nerve, J. Physiol., 117, 500-544, (1952)

[26] Holzapfel, G. A.; Ogden, R. W., Constitutive modelling of passive myocardiuma structurally based framework for material characterization, Philos. Trans. Ser. A, Math., Phys., Eng. Sci., 367, 3445-3475, (2009) · Zbl 1185.74060

[27] Katz, A. M., Physiology of the heart, (2011), Lippincott Williams & Wilkins Philadelphia

[28] Keener, J. P.; Sneyd, J., Mathematical physiology, (1998), Springer New York · Zbl 0913.92009

[29] Keldermann, R.; Nash, M.; Panfilov, A., Pacemakers in a reaction-diffusion mechanics system, J. Stat. Phys., 128, 375-392, (2007) · Zbl 1115.92004

[30] Klabunde, R. E., Cardiovascular physiology concepts, (2005), Lippincott Williams & Wilkins Philadelphia

[31] Kohl, P.; Hunter, P.; Noble, D., Stretch-induced changes in heart rate and rhythmclinical observations, experiments and mathematical models, Prog. Biophys. Mol. Biol., 71, 91-138, (1999)

[32] Kotikanyadanam, M.; Göktepe, S.; Kuhl, E., Computational modeling of electrocardiogramsa finite element approach towards cardiac excitation, Int. J. Numer. Methods Biomed. Eng., 26, 524-533, (2010) · Zbl 1187.92062

[33] Kröner, E., Allgemeine kontinuumstheorie der versetzungen und eigenspannungen, Arch. Rat. Mech. Anal., 4, 273-334, (1960) · Zbl 0090.17601

[34] Lafortune, P.; Arís, R.; Vázquez, M.; Houzeaux, G., Coupled electromechanical model of the heartparallel finite element formulation, Int. J. Numer. Methods Biomed. Eng., 28, 72-86, (2012) · Zbl 1242.92015

[35] Lee, E. H., Elastic-plastic deformation at finite strain, ASME J. Appl. Mech., 36, 1-6, (1969) · Zbl 0179.55603

[36] Levy, M. N.; Koeppen, B. M.; Stanton, B. A., Berne and levy principles of physiology, (2006), Elsevier Science Health Science Division Philadelphia

[37] Luo, C. H.; Rudy, Y., A model of the ventricular cardiac action potential—depolarization, repolarization, and their interaction, Circ. Res., 68, 1501-1526, (1991)

[38] Menzel, A., A fibre reorientation model for orthotropic multiplicative growth, Biomech. Model. Mechanobiol., 6, 303-320, (2007)

[39] Menzel, A.; Steinmann, P., On the spatial formulation of anisotropic multiplicative elasto-plasticity, Comput. Methods Appl. Mech. Eng., 192, 3431-3470, (2003) · Zbl 1054.74533

[40] Menzel, A.; Steinmann, P., A view on anisotropic finite hyper-elasticity, Eur. J. Mech.—A/Solids, 22, 71-87, (2003) · Zbl 1026.74013

[41] Nagumo, J.; Arimoto, S.; Yoshizawa, S., An active pulse transmission line simulating nerve axon, Proc. IRE, 50, 2061-2070, (1962)

[42] Nardinocchi, P.; Teresi, L., On the active response of soft living tissues, J. Elast., 88, 27-39, (2007) · Zbl 1115.74349

[43] Nash, M. P.; Panfilov, A. V., Electromechanical model of excitable tissue to study reentrant cardiac arrhythmias, Prog. Biophys. Mol. Biol., 85, 501-522, (2004)

[44] Nickerson, D.; Nash, M.; Nielsen, P.; Smith, N.; Hunter, P., Computational multiscale modeling in the IUPS physiome

projectmodeling cardiac electromechanics-author bios, Syst. Biol., 50, (2006)

[45] Niederer, S. A.; Smith, N. P., An improved numerical method for strong coupling of excitation and contraction models in the heart, Prog. Biophys. Mol. Biol., 96, 90-111, (2008)

[46] Nielsen, P. M.; Grice, I. J.L.; Smaill, B. H.; Hunter, P. J., Mathematical model of geometry and fibrous structure of the heart, Am. J. Physiol., 260, H1365-H1378, (1991)

[47] Nobile, F.; Quarteroni, A.; Ruiz-Baier, R., An active strain electromechanical model for cardiac tissue, Int. J. Numer. Methods Biomed. Eng., 28, 52-71, (2012) · Zbl 1242.92016

[48] Noble, D., A modification of the Hodgkin-Huxley equations applicable to purkinje fibre action and pacemaker potentials, J. Physiol., 160, 317-352, (1962)

[49] Opie, L. H., Heart physiology: from cell to circulation, (2004), Lippincott Williams & Wilkins Philadelphia

[50] Panfilov, A. V.; Keldermann, R. H.; Nash, M. P., Self-organized pacemakers in a coupled reaction-diffusion-mechanics system, Phys. Rev. Lett., 95, (2005), pp. 258104-1-258014-4

[51] Pelce, P.; Sun, J.; Langeveld, C., A simple model for excitation-contraction coupling in the heart, Chaos, Solitons and Fractals, 5, 383-391, (1995) · Zbl 0925.92052

[52] Pope, A. J.; Sands, G. B.; Smaill, B. H.; LeGrice, I. J., Three-dimensional transmural organization of perimysial collagen in the heart, Am. J. Physiol. Heart Circ. Physiol., 295, H1243-H1252, (2008)

[53] Pullan, A. J.; Buist, M. L.; Cheng, L. K., Mathematical modeling the electrical activity of the heart, (2005), World Scientific Singapore · Zbl 1120.92015

[54] Rohmer, D.; Sitek, A.; Gullberg, G. T., Reconstruction and visualization of fiber and laminar structure in the normal human heart from ex vivo diffusion tensor magnetic resonance imaging (DTMRI) data, Investig. Radiol., 42, 777-789, (2007)

[55] Rossi, S.; Ruiz-Baier, R.; Pavarino, L. F.; Quarteroni, A., Orthotropic active strain models for the numerical simulation of cardiac biomechanics, Int. J. Numer. Methods Biomed. Eng., 28, 761-788, (2012)

[56] Sachse, F. B., Computational cardiology: modeling of anatomy, electrophysiology, and mechanics, (2004), Springer-Verlag Berlin, Heidelberg · Zbl 1051.92025

[57] Sermesant, M.; Rhode, K.; Sanchez-Ortiz, G.; Camara, O.; Andriantsimiavona, R.; Hegde, S.; Rueckert, D.; Lambiase, P.; Bucknall, C.; Rosenthal, E.; Delingette, H.; Hill, D.; Ayache, N.; Razavi, R., Simulation of cardiac pathologies using an electromechanical biventricular model and XMR interventional imaging, Med. Image Anal., 9, 467-480, (2005)

[58] Sidoroff, F., Un modèle viscoélastique non linéaire avec configuration intermédiaire, J. Méc., 13, 679-713, (1974) · Zbl 0321.73029

[59] Stälhand, J.; Klarbring, A.; Holzapfel, G., A mechanochemical 3D continuum model for smooth muscle contraction under finite strains, J. Theor. Biol., 268, 120-130, (2011)

[60] Tusscher, K. H.W. J.T.; Panfilov, A. V., Modelling of the ventricular conduction system, Prog. Biophys. Mol. Biol., 96, 152-170, (2008)

[61] Wong, J.; Göktepe, S.; Kuhl, E., Computational modeling of electrochemical couplinga novel finite element approach towards ionic models for cardiac electrophysiology, Comput. Methods Appl. Mech. Eng., 200, 3139-3158, (2011) · Zbl 1230.92013

[62] Wong, J.; Göktepe, S.; Kuhl, E., Computational modeling of chemo-electro-mechanical couplinga novel implicit monolithic finite element approach, Int. J. Numer. Methods Biomed. Eng., 29, 1104-1133, (2013)