Neural networks based real-time simulations of cardiac electromechanics

Francesco Regazzoni * **Matteo Salvador** * **Luca Dedè** *
Alfio Quarteroni *,**

* *MOX - Dipartimento di Matematica, Politecnico di Milano, P.zza Leonardo da Vinci 32, 20133 Milano, Italy.*
** *Mathematics Institute, École Polytechnique Fédérale de Lausanne, Av. Piccard, CH-1015 Lausanne, Switzerland (Professor Emeritus).*

Abstract: We propose a non-intrusive method, based on Artificial Neural Networks (ANNs), that builds reduced-order models (ROMs) approximating the dynamics of 3D cardiac electromechanics. Our Machine Learning method allows for real-time numerical simulations of the cardiac function, accounting for the dependence on a set of parameters associated with the full-order model (FOM) to be surrogated. The ANN-based ROM is trained from a collection of pressure-volume transients obtained through the FOM and it can then be coupled with hemodynamic models for the blood circulation external to the heart, in the same manner as the original electromechanical model, but at a dramatically lower computational cost. We demonstrate the effectiveness of the proposed method in two relevant contexts in cardiac modeling. First, we employ the ANN-based ROM to perform a global sensitivity analysis on both the electromechanical and hemodynamic models. Second, we perform a Bayesian estimation of two parameters starting from noisy measurements of two scalar outputs. In both these cases, replacing the FOM of cardiac electromechanics with the ANN-based ROM makes it possible to perform in a few hours of computational time the numerical simulations that would be unaffordable if carried out with the FOM, because of their overwhelming computational cost.

Keywords: Cardiac Electromechanics, Machine Learning, Reduced Order Modeling, Global Sensitivity Analysis, Bayesian Parameter Estimation

1. INTRODUCTION

The clinical exploitation of cardiac numerical simulations is seriously hampered by their overwhelming computational cost (several hours of computational time even on supercomputer platforms, see e.g. Quarteroni et al. (2019)). A promising approach to address this issue is to replace the computationally expensive cardiac electromechanical model, say the full-order model (FOM), with a reduced version of it, the reduced-order model (ROM), to be called any time new parameters come in. The ROM is built from a database of numerical simulations obtained by solving the FOM.

Recently, this framework has been applied in the context of cardiac modeling, primarily by using Machine Learning algorithms, including Gaussian Process emulators (GPEs) and Artificial Neural Networks (ANNs) (see e.g. Dabiri et al. (2019); Longobardi et al. (2020)). These emulators are trained to fit the map that links the model parameters with a set of scalar outputs of interest, known as quantities of interest (QoIs), which are clinically meaningful biomarkers.

⋆ This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 740132, iHEART - An Integrated Heart Model for the simulation of the cardiac function, P.I. Prof. A. Quarteroni).

2. METHODS

We propose a Machine Learning method to build a ROM of cardiac electromechanical models, which differs in many respects from existing approaches. We rely on the ANN-based method that we proposed in Regazzoni et al. (2019), which can learn a time-dependent differential equation from a collection of input-output pairs. In contrast to existing approaches, we only surrogate the time-dependent pressure-volume relationship of a cardiac chamber, while we do not reduce the model describing external circulation (see Fig. 1). The latter is indeed either a low dimensional 0D windkessel or closed-loop circulation model comprised of a few state variables (up to two dozens), which does not require further reduction. Unlike emulators, for which the online phase consists in evaluations of the map linking model parameters to QoIs, with our approach the online phase consists instead in numerical simulations, in which the ANN-based ROM of the electromechanical model is coupled with the circulation model, at a very low computational cost.

Our ANN-based ROM consists of a system of Ordinary Differential Equations (ODEs), whose right-hand side is represented by an ANN. The inputs of the ANN are (1) the state variables of the ROM, whose dimension is one of the hyper-parameters of the model; (2) the blood pressure at the current time, that is an input for the

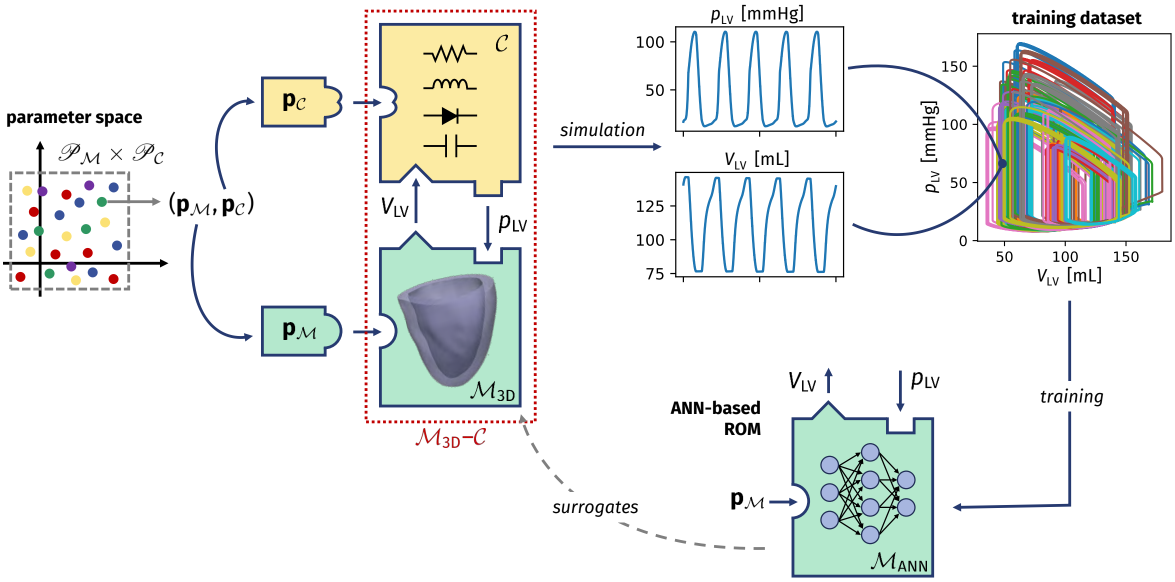

Fig. 1. The training data are generated by sampling the parameter space and by solving the electromechanical model $\mathcal{M}_{3D}$, coupled with the circulation model $\mathcal{C}$, for each parameter instance. Then, once the ANN-based ROM ($\mathcal{M}_{ANN}$) has been trained, it can be coupled to the model $\mathcal{C}$, thus surrogating the $\mathcal{M}_{3D}$ model.

FOM; (3) the parameters of the FOM (e.g. fiber direction, electrical conductivities, active contractility, stiffness of the myocardium); (4) the coordinates of a point that moves on a unitary circumference with the same frequency of the heartbeat, in order to take into account the periodicity of the FOM. The output of the ANN consists instead in the time-derivative of the state variables. By numerically solving this system of ODEs, it is possible to simulate the cardiac dynamics described by the ROM. To train the weights and the biases of the ANN associated with the ROM, we use the Machine Learning algorithm proposed in Regazzoni et al. (2019) by exploiting the open-source library accompanying the manuscript itself.

3. RESULTS

We present two test cases in which we employ the ANN-based ROM. We carry out a global sensitivity analysis to assess the influence of the parameters of the electromechanical and hemodynamic models on a list of outputs of clinical interest. Then, we perform a Bayesian estimation of a couple of parameters (belonging to the electromechanical and hemodynamic models, respectively), starting from the noisy measurement of a couple of scalar quantities (namely maximum and minimum arterial pressure). In both the cases, performing through the FOM the large number of numerical simulations that are needed would not have been possible, due to their high computational cost (it would in fact have taken tens of years on a supercomputer platform). Replacing the FOM with its ANN-based surrogate allowed us to obtain the results in a few hours of computation. By taking into account that the generation of the numerical simulations contained in the training set required less than 7 days on the same computational platform, our ANN-based ROM allowed us to reduce the total computational time by more than 3'000 times.

4. CONCLUSIONS

We presented a Machine Learning algorithm to build ANN-based ROMs of cardiac electromechanical models. Our algorithm is capable of learning, on the basis of pressure and volume transients generated with the FOM, a system of differential equations that approximate the dynamics of the cardiac chamber to be surrogated. This differential equation, linking pressure and volume of a cardiac chamber, is coupled with lumped-parameter models of cardiac hemodynamics, thus allowing for the simulation of the cardiac function at a dramatically reduced computational cost with respect to the original FOM. As a matter of fact, our ROM permits to perform numerical simulations in real-time. Moreover, thanks to its non-intrusive nature, the proposed algorithm can be easily applied to other electromechanical models besides the one considered in this work.

REFERENCES

Dabiri, Y., Van der Velden, A., Sack, K.L., Choy, J.S., Kassab, G.S., and Guccione, J.M. (2019). Prediction of left ventricular mechanics using machine learning. *Frontiers in physics*, 7, 117.

Longobardi, S., Lewalle, A., Coveney, S., Sjaastad, I., Espe, E.K.S., Louch, W.E., Musante, C.J., Sher, A., and Niederer, S.A. (2020). Predicting left ventricular contractile function via gaussian process emulation in aortic-banded rats. *Philosophical Transactions of the Royal Society A*, 378(2173), 20190334.

Quarteroni, A., Dedè, L., Manzoni, A., and Vergara, C. (2019). *Mathematical modelling of the human cardiovascular system: data, numerical approximation, clinical applications*. Cambridge Monographs on Applied and Computational Mathematics. Cambridge University Press.

Regazzoni, F., Dedè, L., and Quarteroni, A. (2019). Machine learning for fast and reliable solution of time-dependent differential equations. *Journal of Computational Physics*, 397, 108852.