Model-based analysis of regional myocardial strains in the context of ischemic heart disease and intraventricular dyssynchrony

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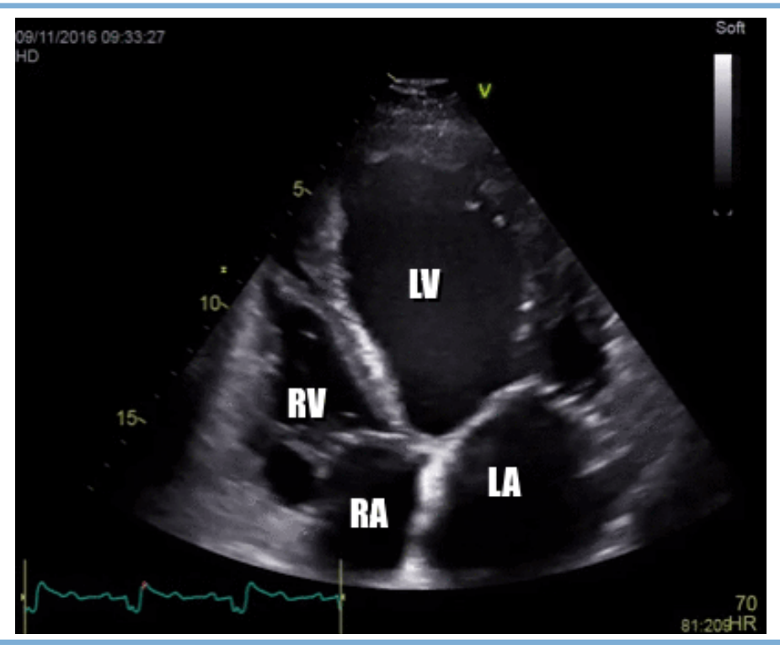
Background

Echocardiography is a clinical tool for diagnosis of heart diseases. **Strains signals** associated with **deformation** can be extracted.

Strains signals can be **difficult to interpret** due to:

- **multi-dimensionnality** (several locations on myocarde)
- **coupling** between electrical, mechanical and hydraulic **activities**.



Objective

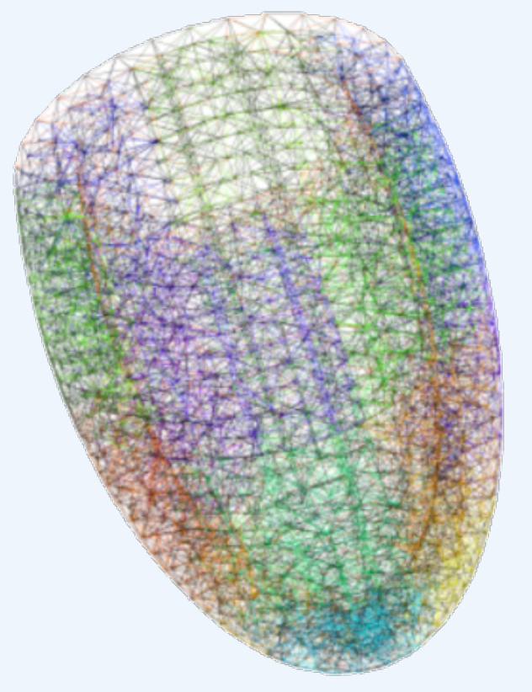
Assess the feasibility of using a left ventricule model in order to **reproduce myocardial strains** in the case of **intraventricular dyssynchrony** and **Ischemic Heart Disease** (IHD).

Model

- **Creation** of the left ventricule **geometry** Ω : truncated ellipsoid.

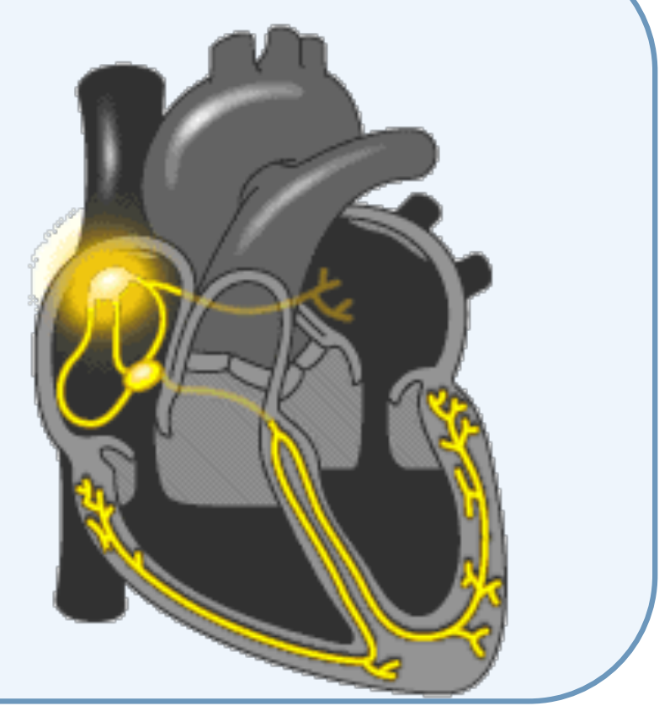
$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} r_s \sin u \ \cos v \\ r_s \sin u \ \cos v \\ r_l \cos u \end{pmatrix}$$

- **Mesh** construction.

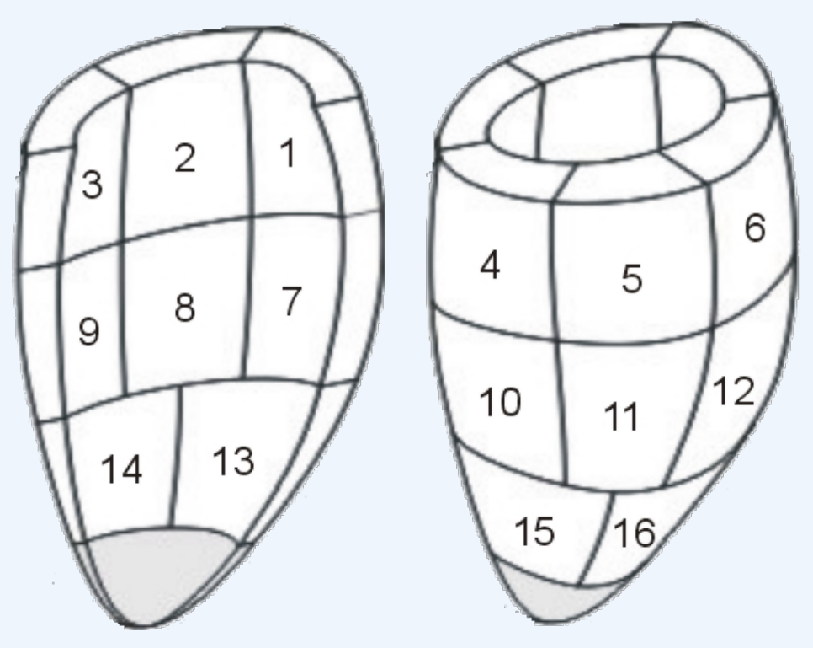


- **Creation** of the **electrical activity** of the left ventricle, resolution of the electrical problem in **finite elements**.
- Find a transmembrane potential $V_m : \Omega \times [T_0, T_{period}] \to \mathbb{R}$, and a ionic variable $w : \Omega \times [T_0, T_{period}] \to \mathbb{R}$, such that:

$$\begin{array}{ll} Div(\sigma_{eq} \nabla V_m) = \chi(C_m \frac{\partial V_m}{\partial t} + I_{ion}(V_m, w) & \text{in } \Omega, \\ \frac{\partial w}{\partial t} = g(V_m, w) & \text{in } \Omega, \\ -(\sigma_{eq} \nabla V_m).\boldsymbol{v} = \begin{cases} I_{stim}(t) & \text{if } t < t_{exc} \\ 0 & \text{else} \end{cases} & \text{in } N_{ext}, \\ V_m(0) = V_m^0 & \text{in } \Omega, \\ w(0) = w^0 & \text{in } \Omega. \end{array}$$



Geometry → Segmentation → Electrical → Fiber → Hemodynamical → Mechanical → Visualization



- **Segmentation** of the left ventricle into 16 segments.

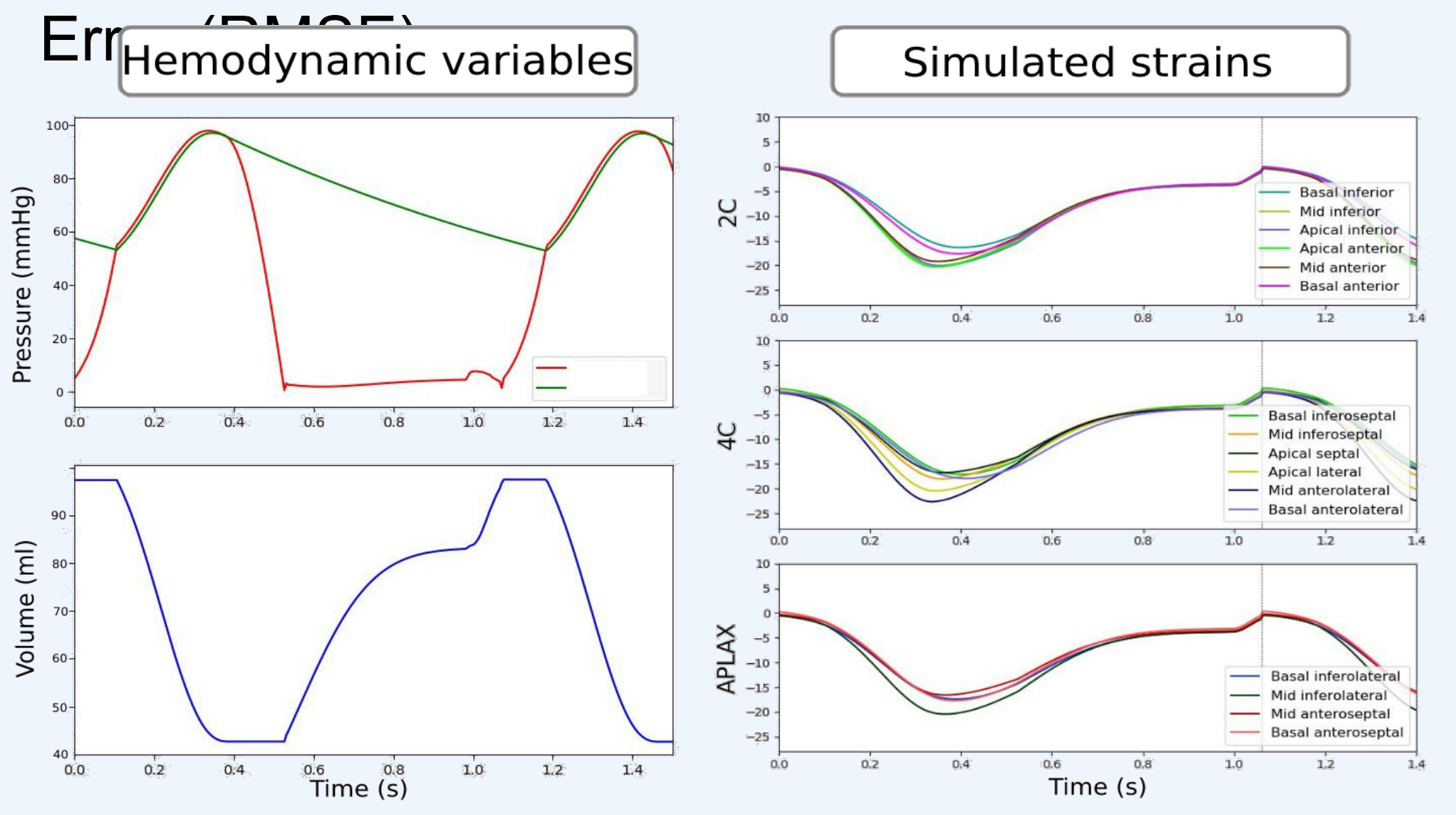
- **Creation** of the **mechanical activity** of the left ventricle, resolution of the mechanical problem in **finite elements**.
- Coupling of electrical activity with mechanical activity, and coupling of blood circulation with mechanical activity of the left ventricle.

- Find a displacement field $\boldsymbol{u} : \Omega \times [T_0, T_{period}] \to \mathbb{R}^d$, and a constraint field $\boldsymbol{\sigma} : \Omega \times [T_0, T_{period}] \to \mathbb{M}^d$:

$$\begin{array}{ll} \boldsymbol{\sigma} = \boldsymbol{\sigma_p} + \sigma_a \boldsymbol{f} \boldsymbol{f}^T & \text{in } \Omega \times [T_0, T_{period}], \\ div \boldsymbol{\sigma}(t) = \boldsymbol{0} & \text{in } \Omega \times [T_0, T_{period}], \\ \boldsymbol{u}(t) = \boldsymbol{u}_{\Gamma_1} & \text{on } \Gamma_{Basis} \times [T_0, T_{period}], \\ \boldsymbol{\sigma}(t) \boldsymbol{v} = \boldsymbol{p}(t) & \text{on } \Gamma_{Endo} \times [T_0, T_{period}], \\ \boldsymbol{\sigma}(t) \boldsymbol{v} = 0 & \text{on } \Gamma_{Epi} \times [T_0, T_{period}]. \end{array}$$

- **Creation** of muscle **fibers.**

- **Visualization** of **strain** curves, comparison with clinical data and calculation of Root Mean Square Error (RMSE).



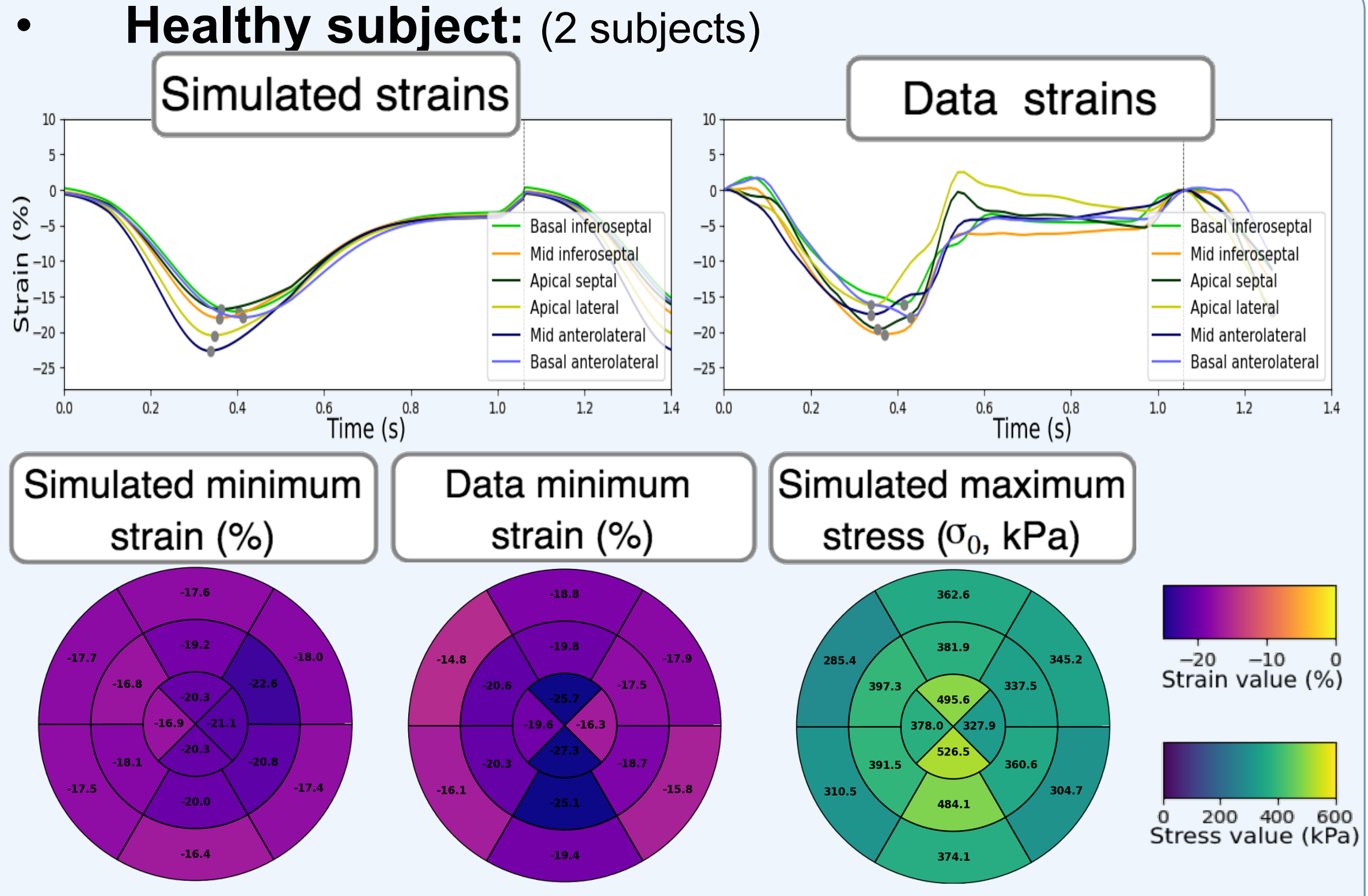
- **Creation** of **blood circulation** in the left ventricle.
- Find the volume scalar fields V_{lv}, V_{la} and V_{ao} such that, where P and Q are pressure and flow:

$$\begin{aligned} e_{la}(t) &= e^{-B_{la}(t - C_{la} - t_{start_{la}})^2}, \\ P_{la} &= (e_{la}(t)(Ela_{max} - Ela_{min}) + Ela_{min})(V_{la} - V_{d_{la}}), \\ e_{lv}(t) &= Ae^{-B_{lv}(t - C_{lv} - t_{start_{lv}})^2}, \\ P_{lv} &= e_{lv}(t) E_{lv}(V_{lv} - V_{d_{lv}}) + (1 - e_{lv}(t)) P_{0_{lv}}(e^{\lambda_{lv}(V_{lv} - V_{0_{lv}})} - 1), \\ P_{ao} &= \frac{V_{ao}}{C_{ao}}, \\ Q_{R_{ao}} &= \frac{P_{ao}}{R_{ao}}, \\ Q_{in\_lv} &= \begin{cases} \frac{P_{la} - P_{lv}}{R_{in\_lv}} & \text{si } P_{lv} < P_{la}, \\ 0 & \text{sinon,} \end{cases} \end{aligned}$$

$$\begin{aligned} Q_{out\_lv} &= \begin{cases} \frac{P_{lv} - P_{ao}}{R_{out\_lv}} & \text{si } P_{lv} > P_{ao}, \\ 0 & \text{sinon,} \end{cases} \\ Q_{R_{la}} &= \frac{P_{in0\_lv} - P_{la}}{R_{la}}, \\ \dot{V}_{lv} &= Q_{in\_lv} - Q_{out\_lv}, \\ \dot{V}_{la} &= Q_{R_{la}} - Q_{in\_lv}, \\ \dot{V}_{ao} &= Q_{out\_lv} - Q_{R_{ao}}. \end{aligned}$$

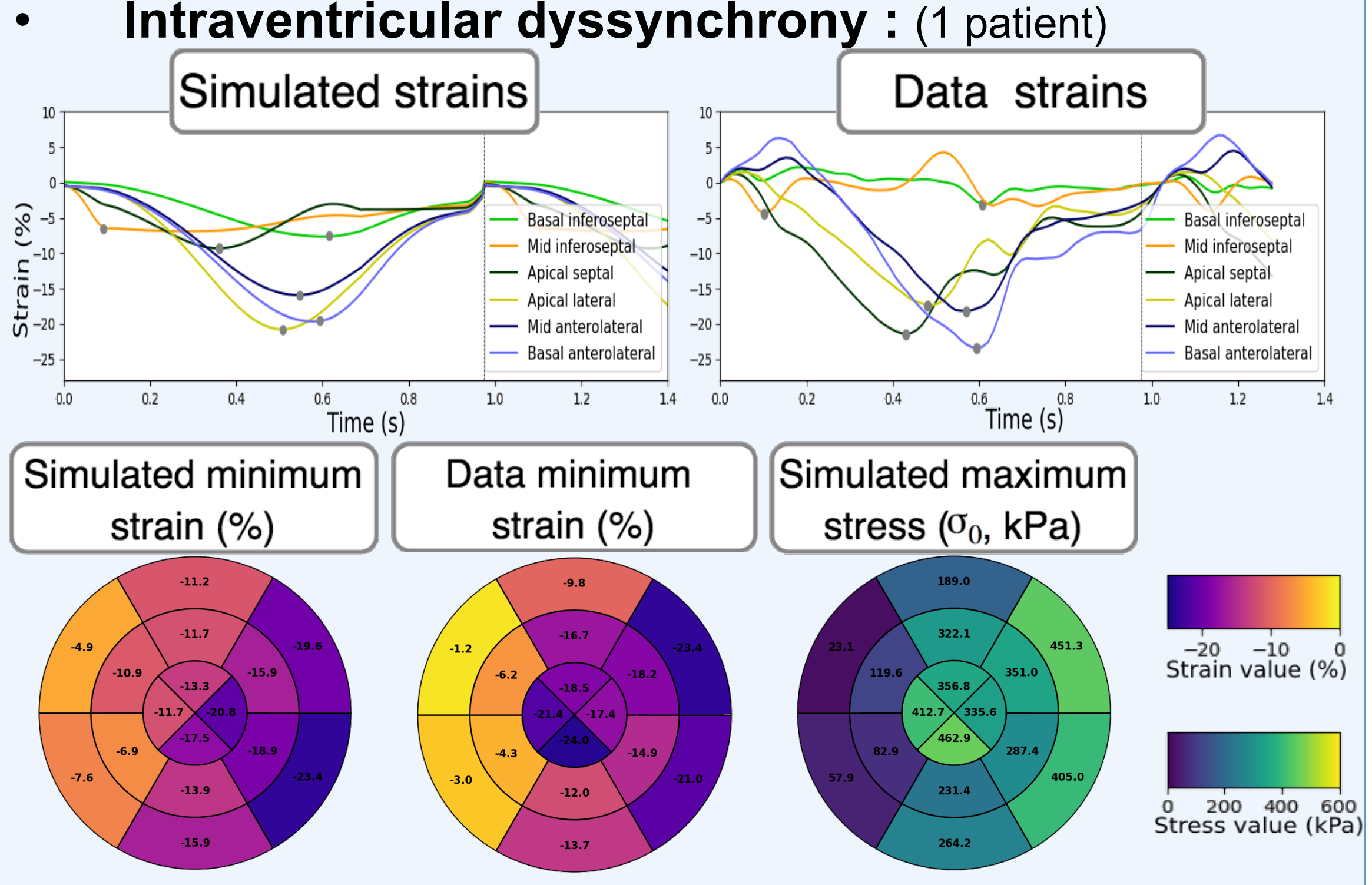
Results

- **Healthy subject:** (2 subjects)



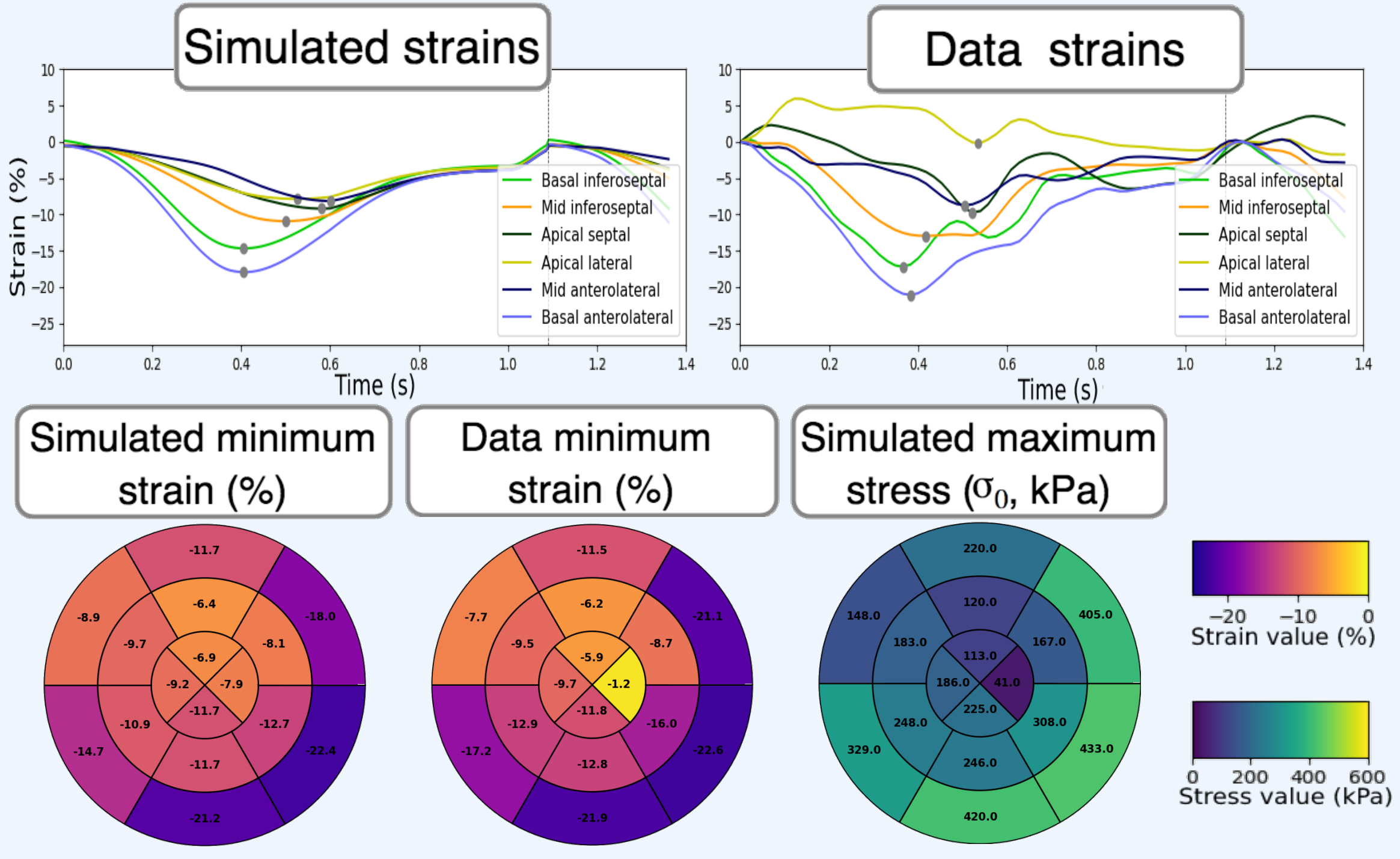
  - RMSE minimum strain: 2.78 % (±0.82).
  - RMSE strain morphology: 4.753 % (±0.33).

- **Intraventricular dyssynchrony :** (1 patient)



  - RMSE minimum strain: 4.44 %.
  - RMSE strain morphology: 5.164 %.

- **Ischemic heart disease :** (2 patients)



  - RMSE minimum strain: 2.52 % (±0.28) .
  - RMSE strain morphology: 5.332 % (±0.08).

Conclusion

- A **close match** is observed between **minimum strains** and **strains morphology** obtained from simulations and clinical data.
- Results show the model ability to simulate jointly the hemodynamic variables and myocardial strain curves during each phase of the cardiac cycle, in context of intraventricular dyssynchrony and IHD cases.

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