International Conference on Computational Science and Engineering

Assessment of regional myocardial work through adjoint-based data assimilation

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Henrik Finsberg

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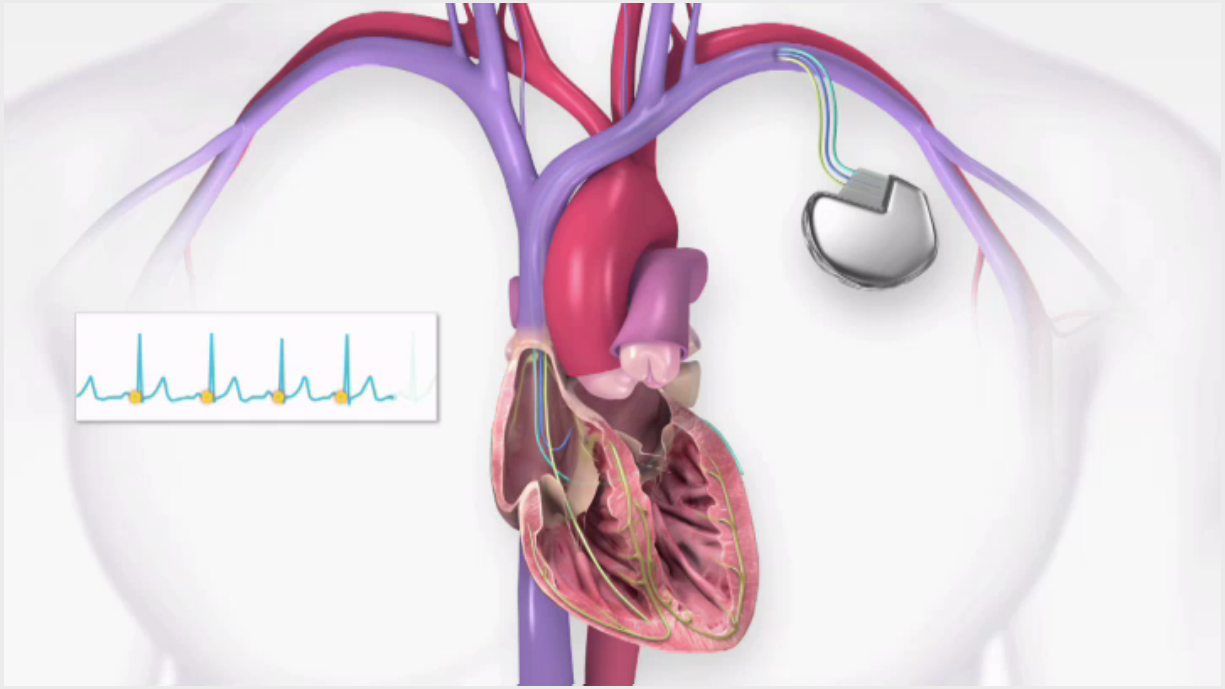
Clinicians need better biomarkers for identifying responders in heart failure treatment



Source: American Heart Asscociation

European Heart Journal – Cardiovascular Imaging (2016) **17**, 624–632
doi:10.1093/ehjci/jew019

Wasted septal work in left ventricular dyssynchrony: a novel principle to predict response to cardiac resynchronization therapy

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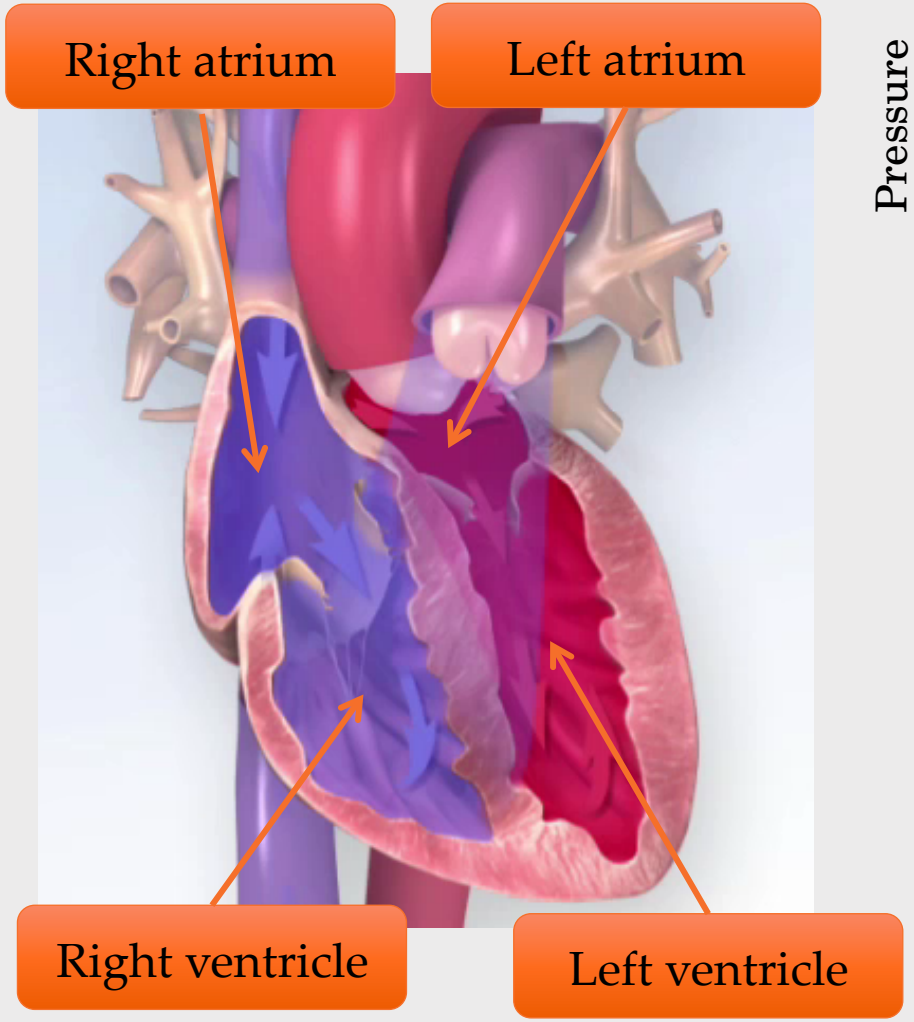
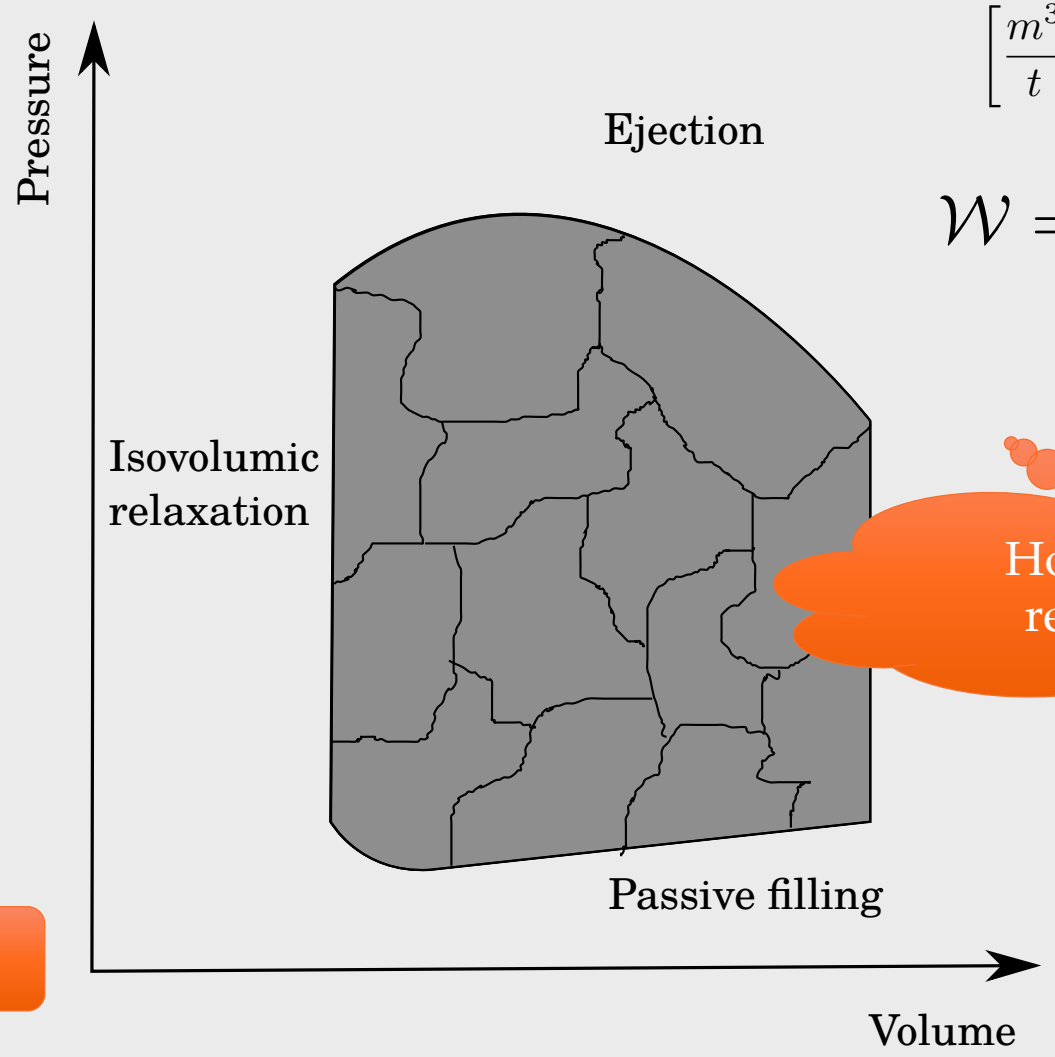
Total myocardial work in the left ventricle can be estimated by the area of the pressure-volume loop



Source: American Heart Association

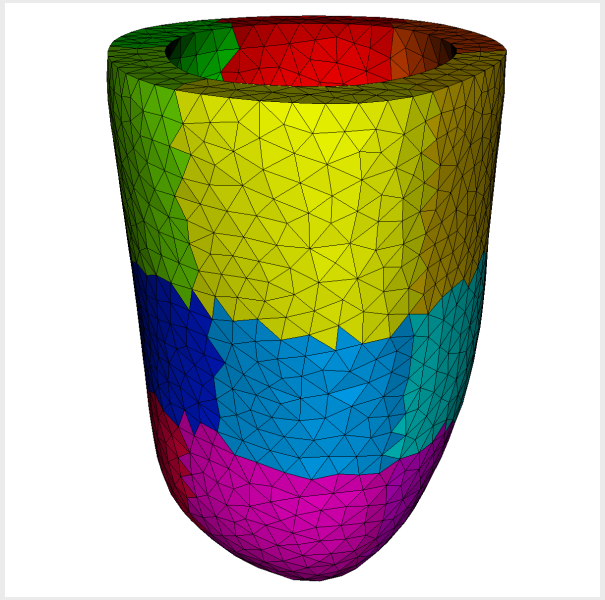


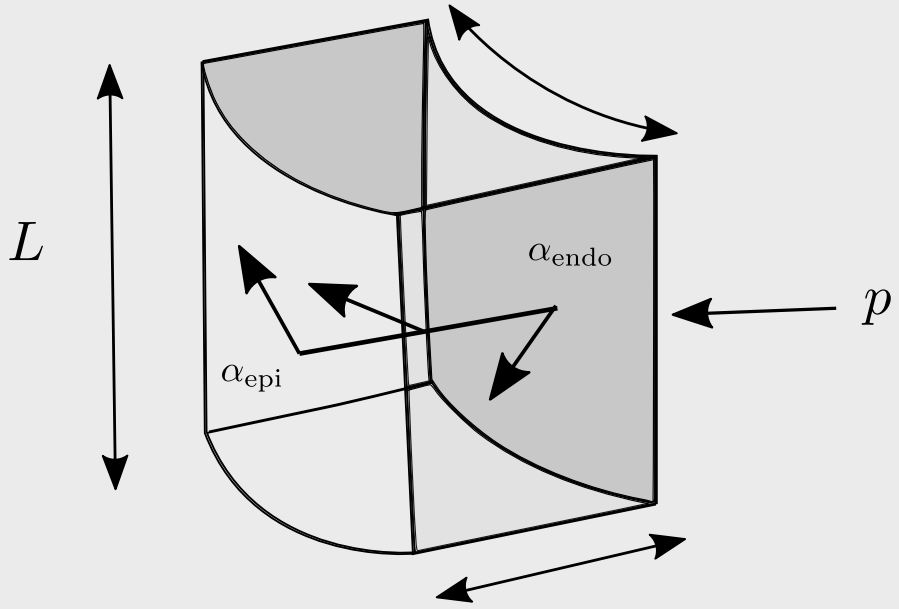
$$\left[\frac{m^3}{t}\cdot \mathrm{Pa}\cdot t\right] = \left[\mathrm{Pa}\cdot m^3\right] = [\mathrm{Joule}]$$

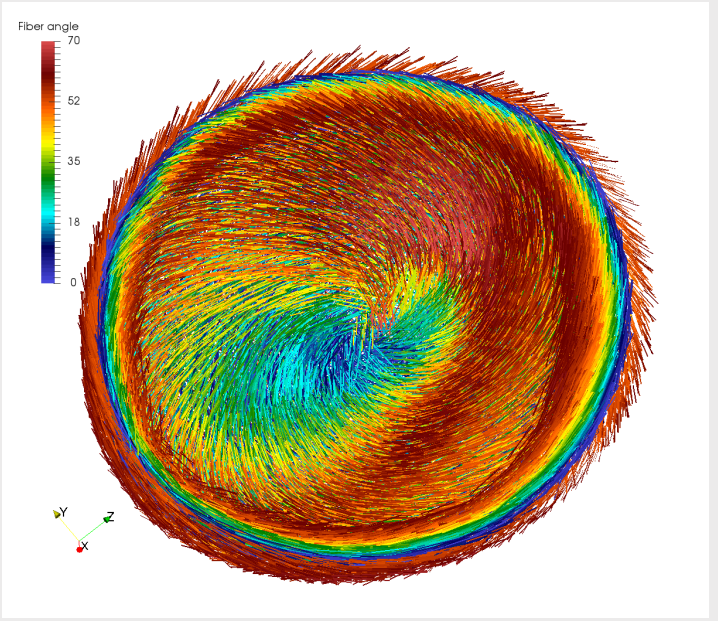
$$\mathcal{W} = \int \frac{\mathrm{d}V}{\mathrm{d}t} P(t)\mathrm{d}t$$

How to compute regional work?

Regional work is estimated in the clinic based on the area of pressure strain loops – reasonable assumption?





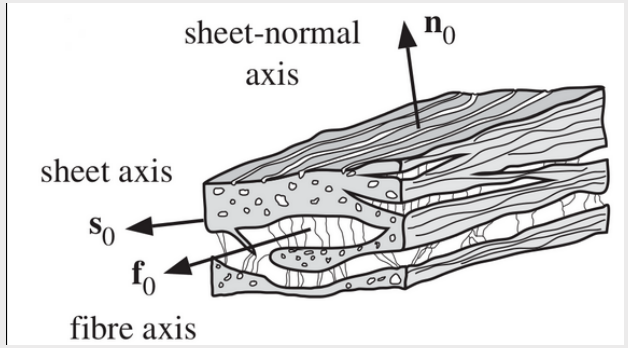


$$V \leftrightarrow \varepsilon = \frac{L - L_0}{L_0} \qquad [\text{Pa} \cdot 1] = [\text{Joule}/m^3]$$

Mathematical models of the heart allow for formulation of realistic constitutive equations in a continuum mechanics framework

Model for the passive tissue

$$\Psi(\overline{\mathbf{C}}) = \frac{a}{2b}\left(e^{b(\bar{I}_1-3)} - 1\right) + \frac{a_f}{2b_f}\left(e^{b_f(\bar{I}_{4\mathbf{f}_0}-1)_+^2} - 1\right)$$

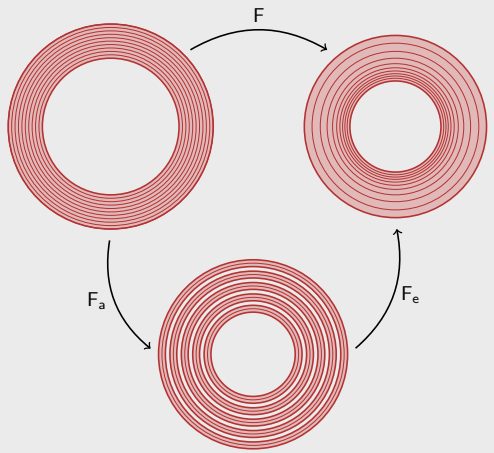


Holzapfel et al.

Model for active contraction

$$\mathbf{F} = \mathbf{F}_e\mathbf{F}_a$$

Pezzuto et al.

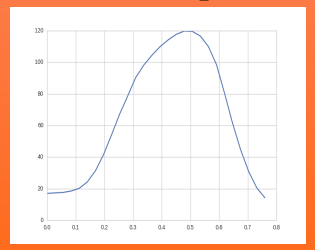


$$\mathbf{F}_a = (1-\gamma)\mathbf{f}_0 \otimes \mathbf{f}_0 + \frac{1}{\sqrt{1-\gamma}}(\mathbf{I} - \mathbf{f}_0 \otimes \mathbf{f}_0)$$

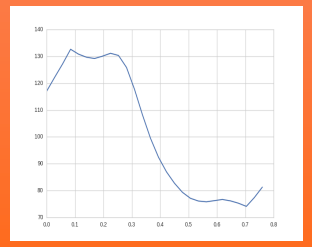
Personalized mechanics models can be created through data assimilation

Non-invasive data from 3D ultrasound

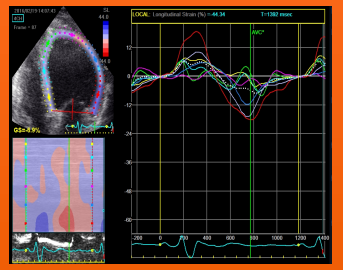
Estimated pressure



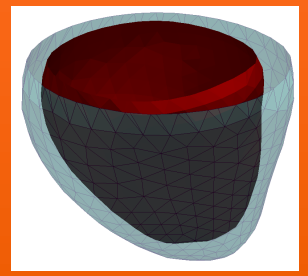
Measured volume



Longitudinal strain



Segmented surfaces



Data assimilation

Minimize difference between model and observations by tuning parameters in the model

Mismatch functional

$$\underset{\mu}{\text{minimize}} \quad \mathcal{J}(\mathbf{w}(\mu), \mu)$$

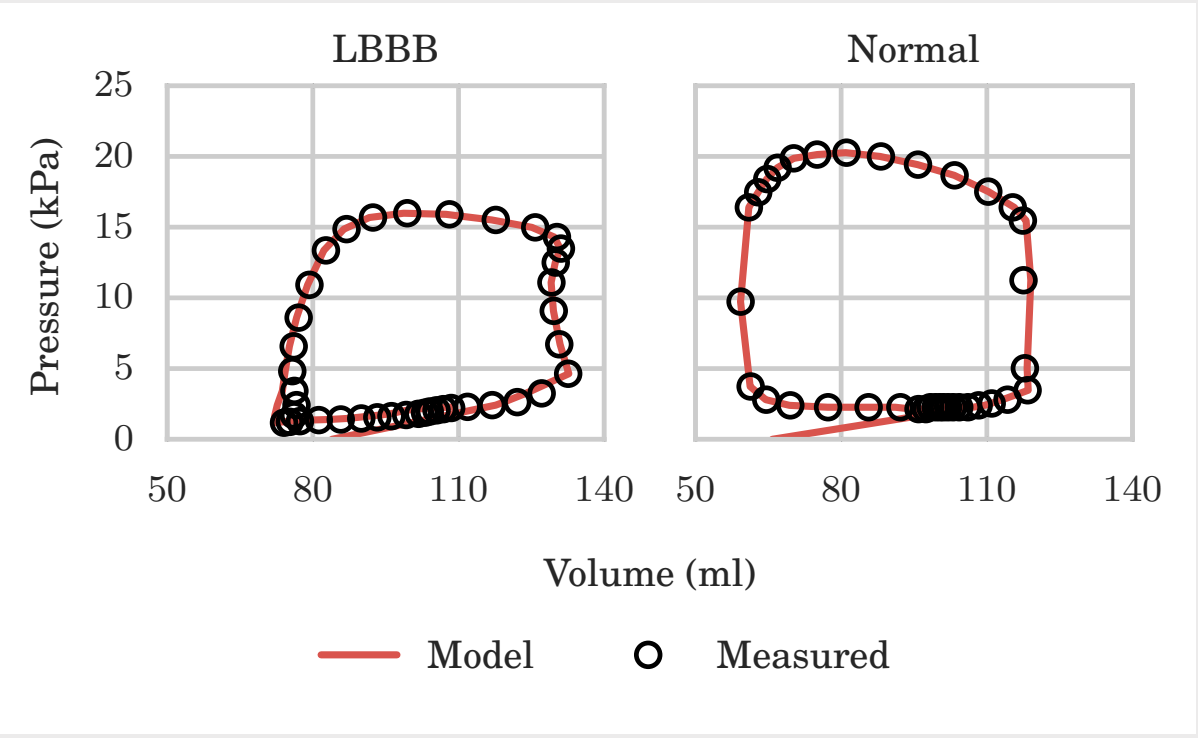
$$\text{subject to} \quad F(\mathbf{w}, \mu) = 0,$$

Force balance equation

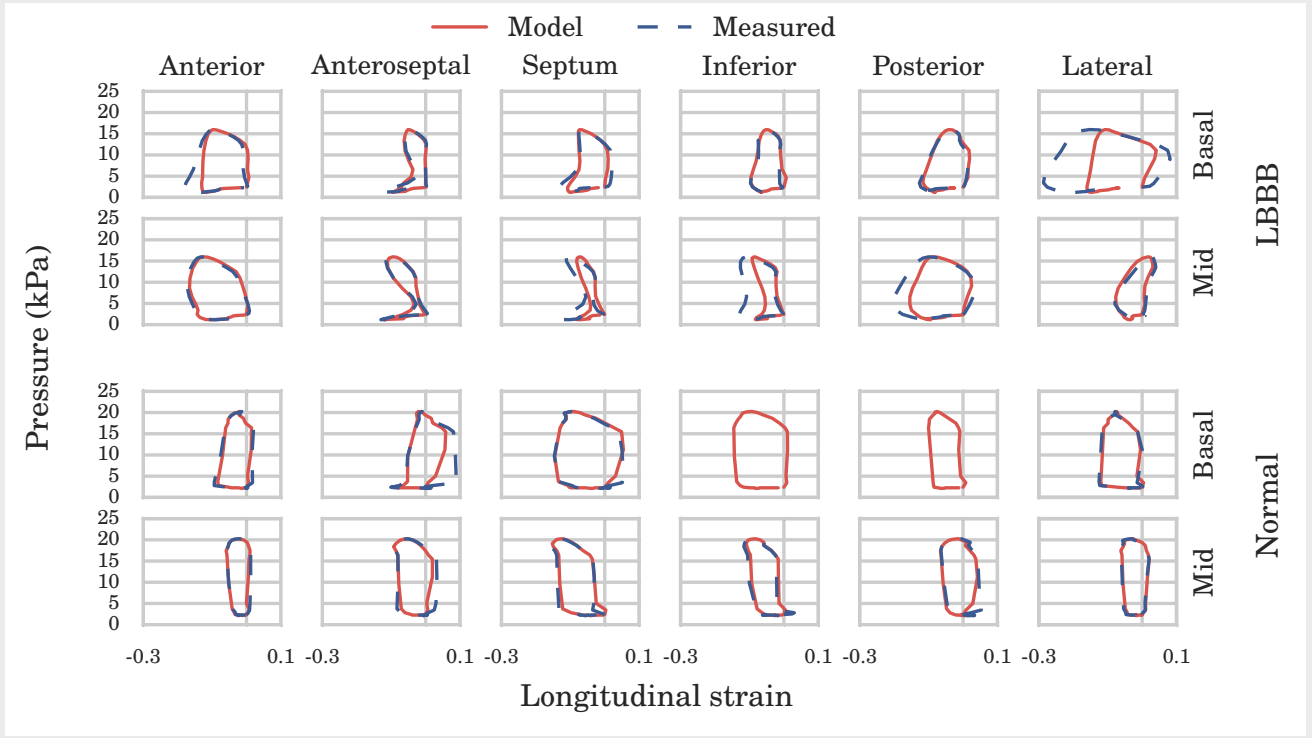
FENICS PROJECT dolfin-adjoint

Excellent fit between measured and simulated data is obtained

Pressure-Volume Loops

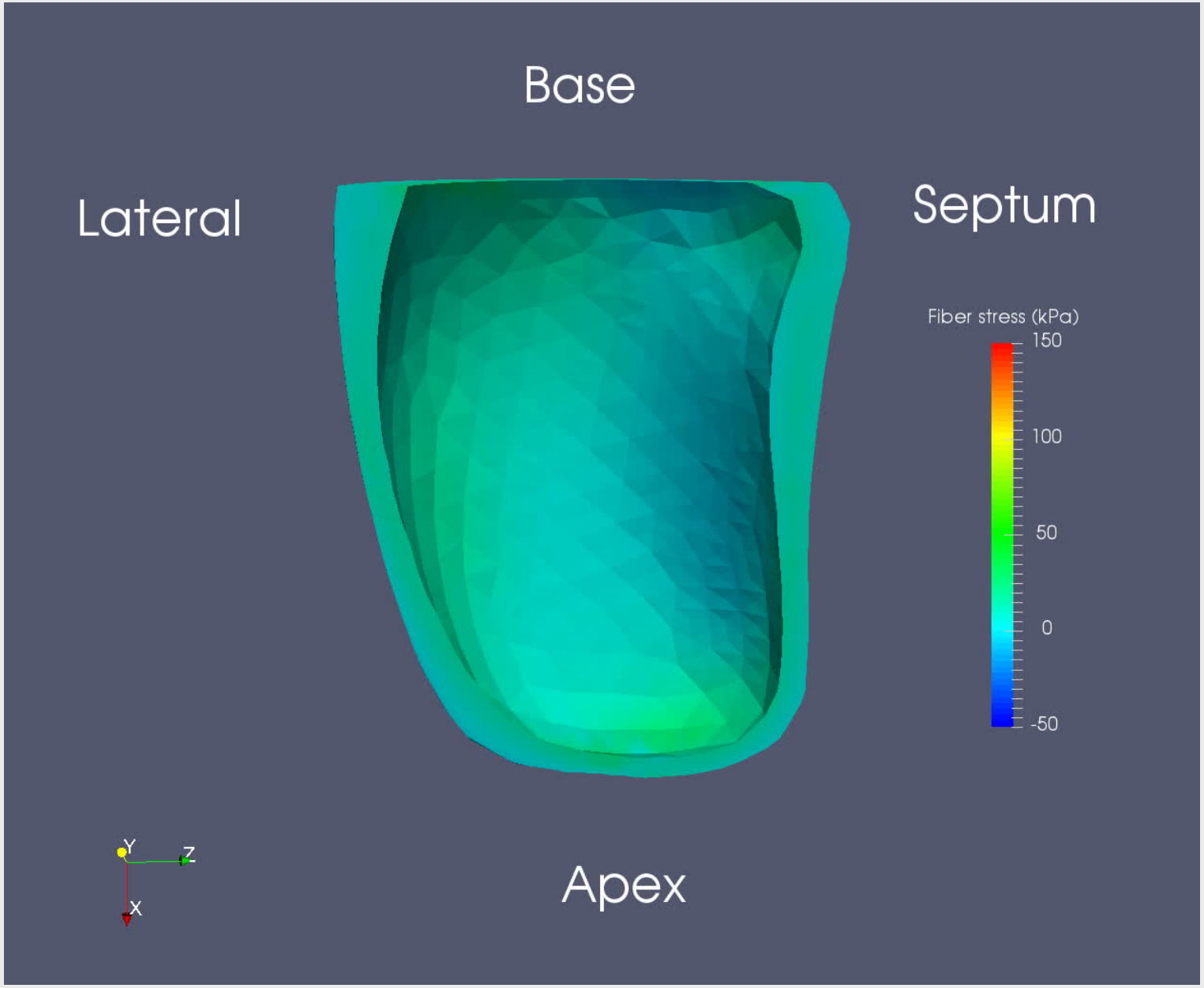


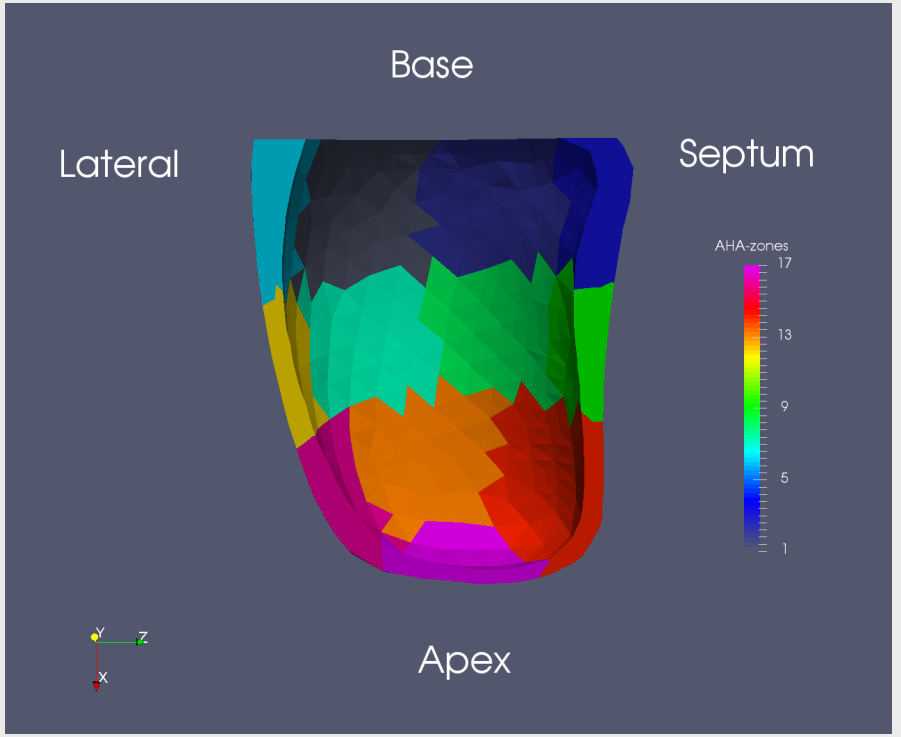
Pressure-Strain Loops



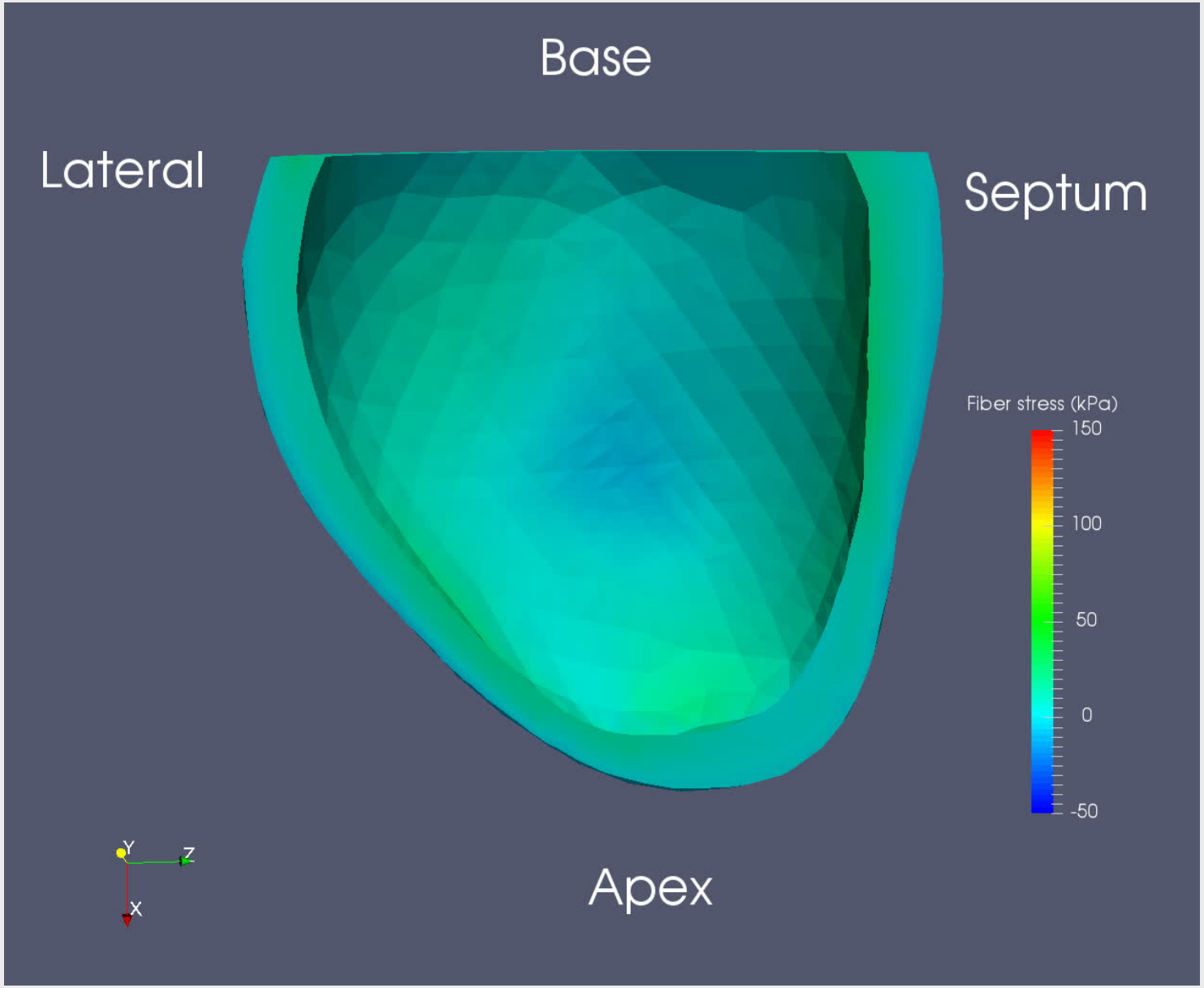
LBBB: patient with dyssynchrony

Normal


Base
Lateral
Septum
Fiber stress (kPa)
150
100
50
0
-50
Y
Z
X
Apex


Base
Lateral
Septum
AHA-zones
17
13
9
5
1
Y
Z
X
Apex

LBBB


Base
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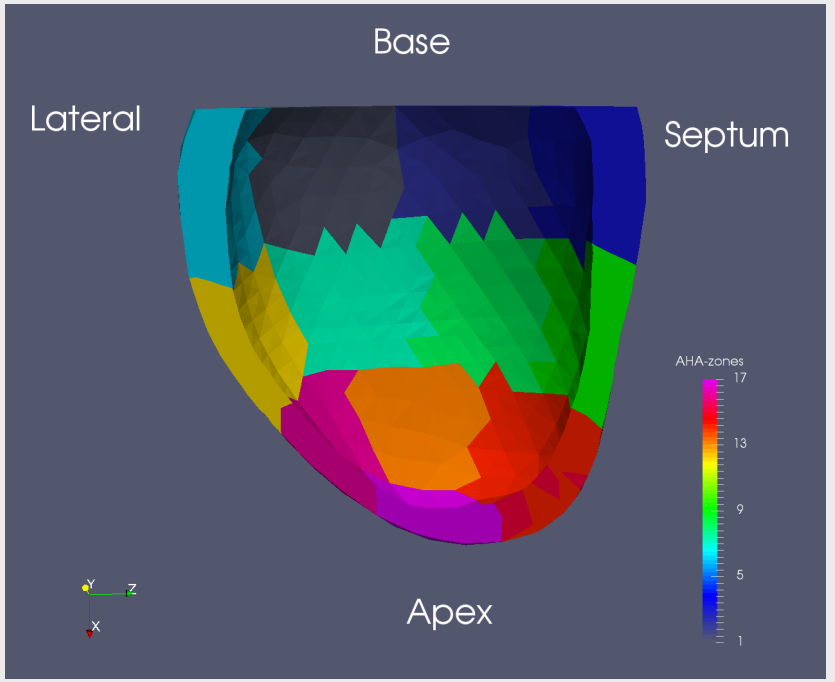

Base
Lateral
Septum
AHA-zones
17
13
9
5
1
Y
Z
X
Apex

The patient specific mechanical models can be used to estimate work

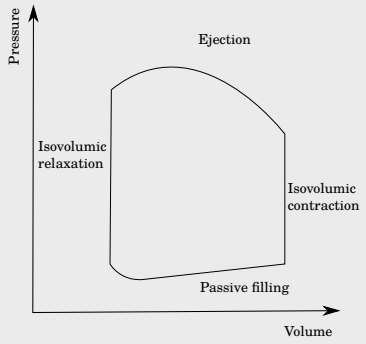
$$\mathcal{W}(t_1, t_2)[\Omega_j] = -\int_{t_1}^{t_2} \int_{\Omega_j} \mathbf{S}(t, \mathbf{X}) : \dot{\mathbf{E}}(t, \mathbf{X}) \mathrm{d}\mathbf{X} \mathrm{d}t$$

Second Piola-Kirchhoff stress tensor: $\mathbf{S}(t, \mathbf{X})$

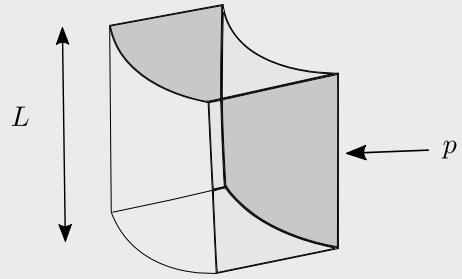
Green-Lagrange strain tensor: $\mathbf{E}(t, \mathbf{X})$

Case	PV area (kW m^{-3})	Full (kW m^{-3})	Fiber (kW m^{-3})	Pressure-GLS (kW m^{-3})
LBBB	8.41	10.60	6.42	1.02
Normal	15.79	16.35	9.59	1.59

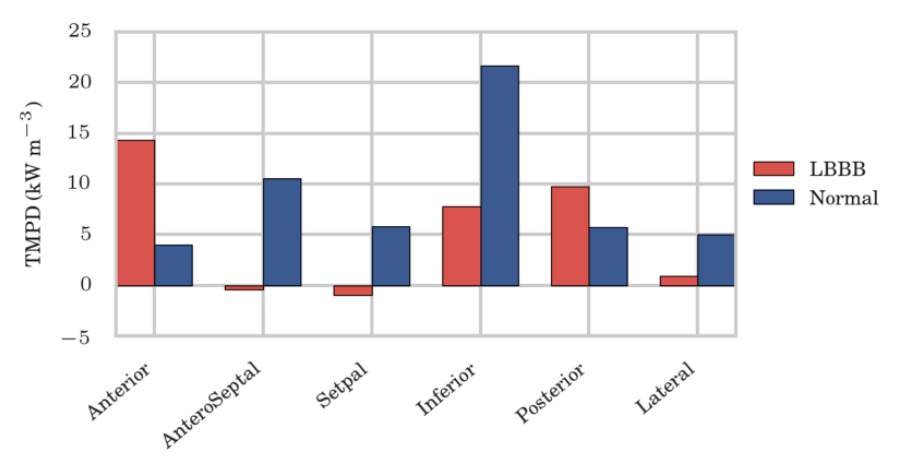
$\mathcal{W}(t_1, t_2)[\Omega_j]/|\Omega_j| \cdot (t_2 - t_1)$



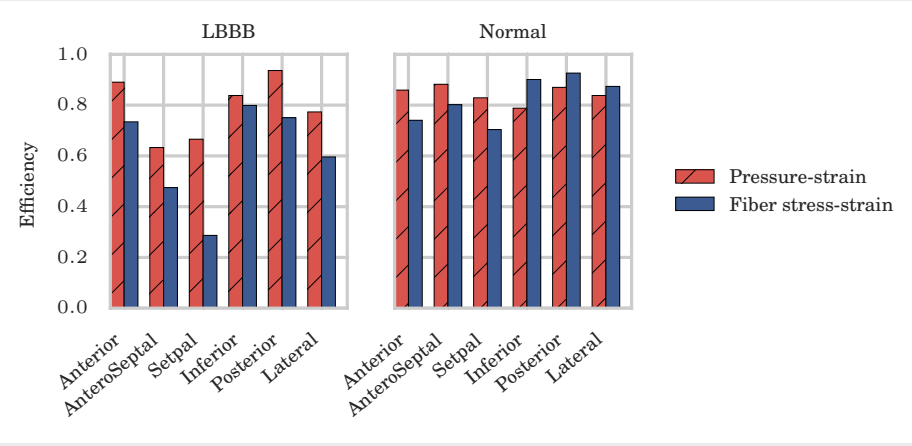
$$\begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{23} & \sigma_{33} \end{pmatrix} \qquad \begin{pmatrix} \sigma_{ff} & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$$



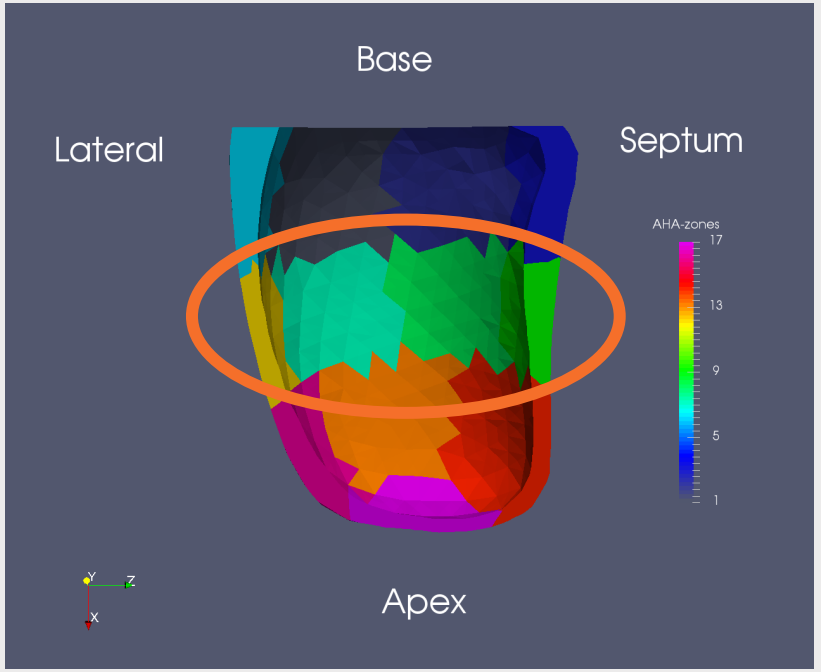
The regional efficiency of each segment show the same trend regardless of how work is estimated



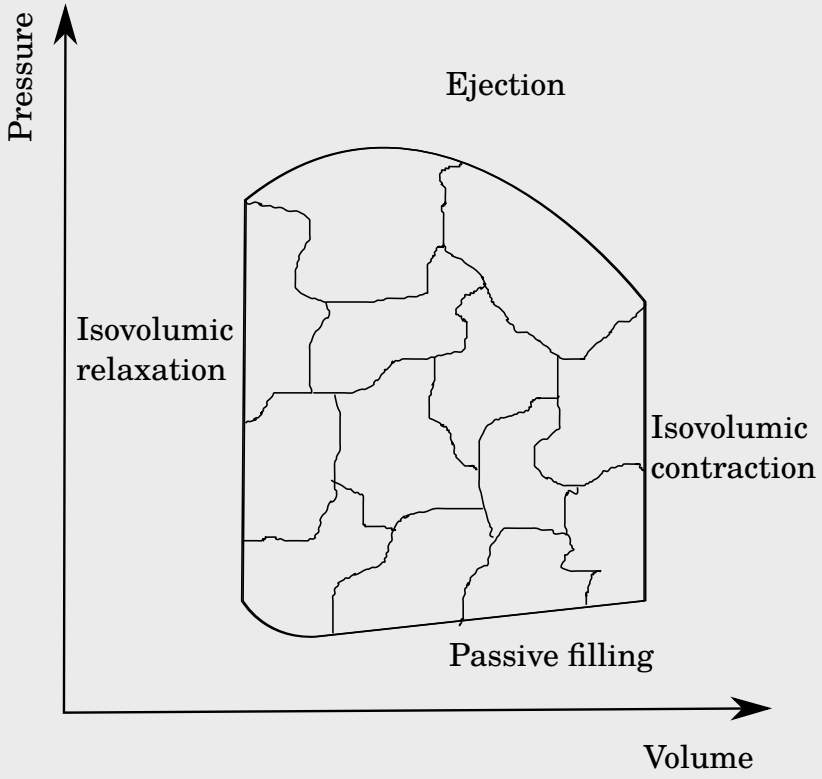
Regional total power density
Positive values indicate generation of work
Negative values indicate work usage

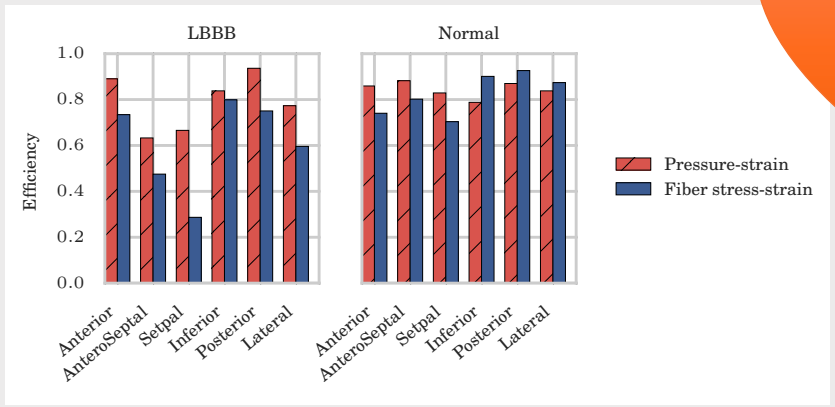


Regional efficiency
Higher values indicate higher efficiency

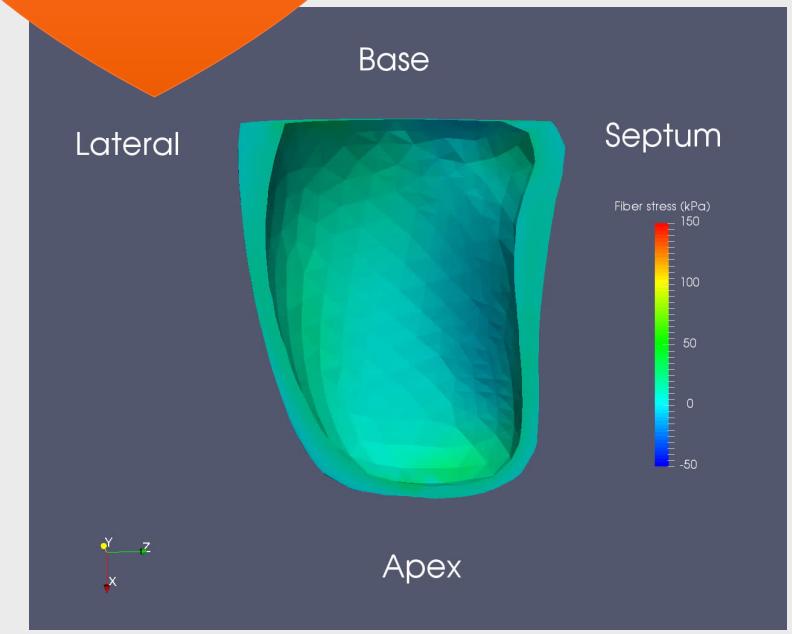


Patient-specific modeling can be used to assess estimates regional myocardial work





Thank you!



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CENTER FOR CARDIOLOGICAL INNOVATION

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