Open-source software for coupling growth and remodeling of tissues with cell signaling pathways

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1-Introduction:

This repository contains the input files required to reproduce nonlinear transient structural mechanics problems presented in Soltany et al. 2023. Input files are provided for reproduction in Python (FEniCS) or Finite Elements for Biomechanics (FEBio). These simulations couple the kinematic growth and remodeling (G&R) of a biological tissue/structure with systems biology and cell signaling pathways. At the cell scale, we implement a system of ordinary differential equations (ODEs) or partial differential equations (PDEs) representing the reactions between the biochemicals causing the growth. We implemented the weak form of the governing continuum mechanics equations using finite element analysis representing the G&R at the tissue level. Three test subjects (cube, aneurysm, and aortic valve) are implemented in the package.

2- Installation:

FEBio installation:

FEBio is available through the FEBio software suite. This includes both FEBio as well as FEBioStudio which provides a GUI to create models.

Model input files have the extension .feb which is based on xml. These can be viewed and edited in FEBioStudio or a text editor. An excellent introduction to FEBio can be found at https://febio.org/knowledgebase/.

The best reference to install FEBio + FEBioStudio: https://febio.org/downloads/
The simulations were generated using a different branch of FEBio than the main build that comes with the FEBio download. The branch used for this software can be built from the repository stored at https://github.com/febiosoftware/FEBio/tree/kinematic-growth-dev

Once built, users can run this version of FEBio via

```
febio4_dev.exe -i [input_file.feb] -noconfig
```

In the future, this branch will be merged into the main branch of FEBio. Additionally, the input files will be added to the FEBio model repository so that users may download models through the FEBioStudio repository interface.

3-Files and folders:

The software contains three folders for the cube, aneurysm, and aortic valve models. All of the codes are implemented in C++. The code can be run in parallel by specifying the number of threads before running the model:

```
$ set OMP_NUM_THREADS=[number_of_threads]
```

Note 1: The aortic valve model was not created for FEBio. To reproduce the aortic valve model, see the instructions for FEniCS.

5- Post-processing:

You can see the results in the open-source software FEBioStudio or ParaView. Model results may be viewed in FEBioStudio by opening the associated ".xplt" file generated by FEBio. To visualize in ParaView, the model must first be opened in FEBio. Once in FEBio, select "Save As" and choose ".vtk" as the file type. A time-series data set can be output by selecting "Export all states" and enabling "output VTK series file." Then, open ParaView and select the .vtk-series file. ParaView can be downloaded at: https://www.paraview.org/download/

Additional steps are needed to see the displacement and the growth for each time span in Paraview. This can be accomplished with the "warp by vector" option in Filters->alphabetical->warp by vector.