Parallel Implementation of a Hybrid Particle-Continuum Finite Element Framework for Blood Clot Biomechanics

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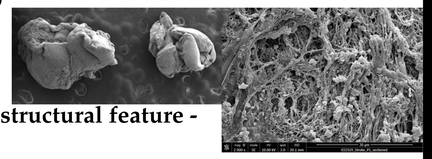
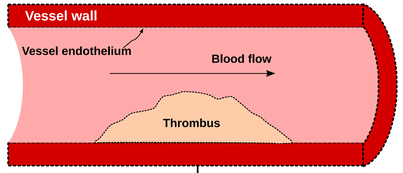
1. Real human blood clots are challenging to model.

- Blood clots are the leading cause of stroke and heart attack.
- Understanding flow around a clot is essential for treatment.
- Real clots have arbitrary shape and heterogeneous microstructure.
- Conventional methods involve creating grids that resolve each microstructural feature - which is expensive.



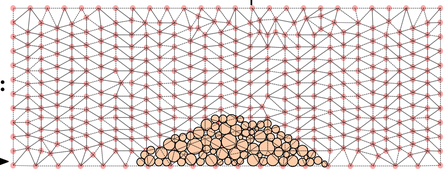
2. Particle-Continuum fictitious domain framework



1. Represent the porous structure as an aggregate of discrete particles/elements.

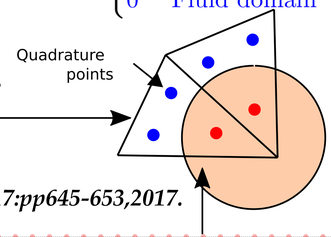
2. Impose the particle onto the background fluid with a fictitious domain force coupling:

$$f(x) = \kappa I(\mathbf{x})(\mathbf{u} - \mathbf{v})$$



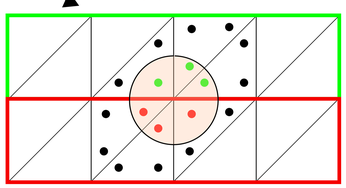
$$I(x) = \begin{cases} 1 & \text{Solid domain} \\ 0 & \text{Fluid domain} \end{cases}$$

3. Fictitious domain term evaluated as discontinuous functions for quadrature within a stabilized finite element method.
Biomech. Model. Mechan., 17:pp645-653,2017.

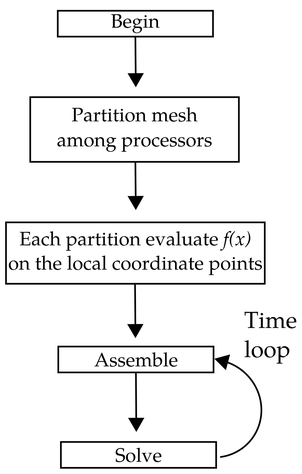


3. Fictitious domain framework shows good scaling behavior.

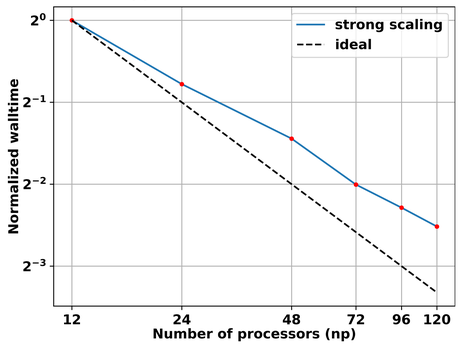
The fictitious domain data is defined on the quadrature points which are partitioned along with the computational domain.



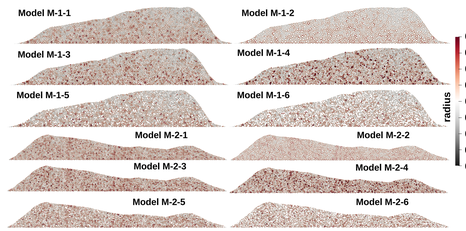
Pseudocode

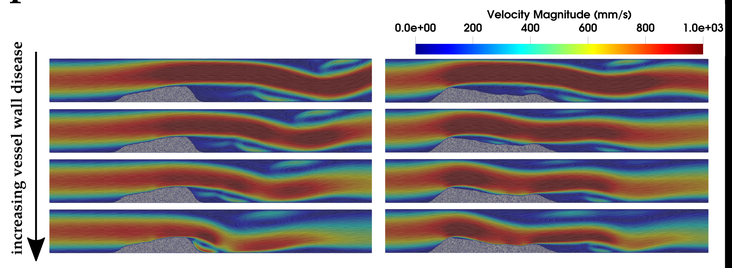


- The framework is implemented with the finite element library: FEniCS *Arch. Num. Soft.,3:pp9-23,2015.*
- It shows good scaling behavior on CU Boulder's RMACC Summit Cluster *Proc. PEAR17:pp7,2017.*



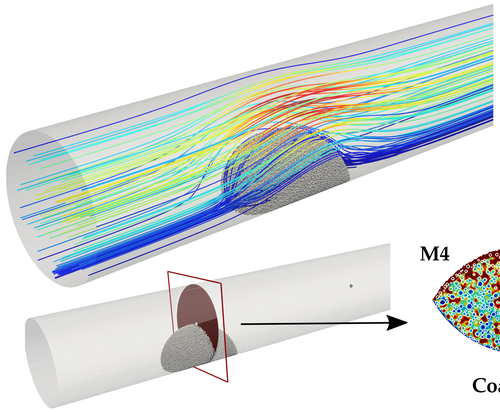
4. Framework enables rapid parametric variation of clot structures.

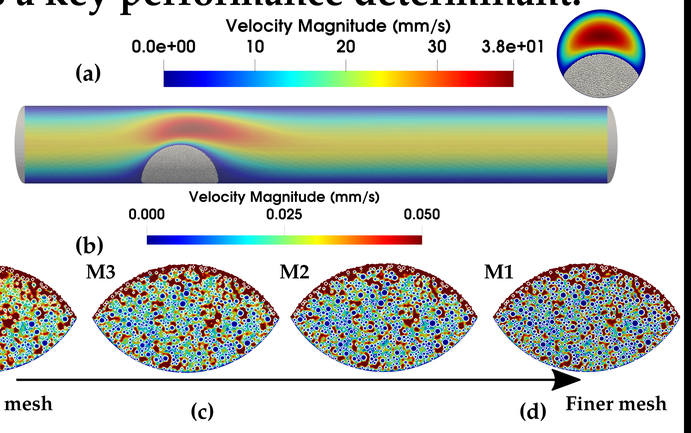




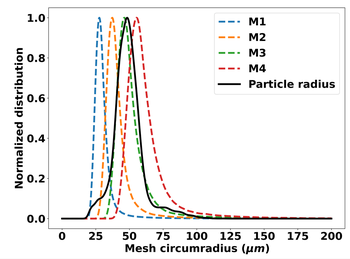
Our framework enables studying flow around realistic blood clots via rapid parametric variations in clot microstructure. Here we performed a systematic study of 48 different clot types (2 clot shape x 4 wall disease state x 6 clot microstructures [left]) to illustrate unsteady hemodynamic phenomena around real arterial clots [right].

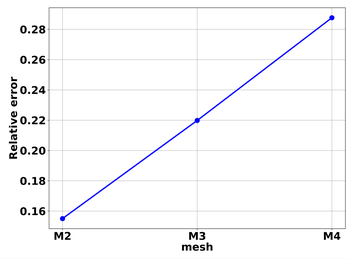
5. Mesh vs particle size ratio is a key performance determinant.





We experimented with varying ratios of mesh size vs particle size in the clot domain which directly indicates particle resolution. Figure (a) shows flow field outside of the clot. Figure (b) shows flow field inside the clot with varying mesh sizes. Figures (c) and (d) show the element size distribution and error relative to the finest mesh (M1) respectively.





6. Concluding remarks

Hybrid particle-continuum framework allow for a robust way to model fluid dynamics in and around a highly heterogeneous porous media (such as blood clots). The framework show good scaling behavior. To recover flow behavior inside the porous media, a sufficiently fine mesh in that domain is still required. This framework enables a parametric study of hemodynamics around varying clot structures. This work is currently under review and a preprint is available: C. Teeraratkul, Z. Irwin, S. C. Shadden, D. Mukherjee, bioRxiv, 2020

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