Supporting Information for

Size and position dependent cytoplasm viscoelasticity through hydrodynamic interactions with the cell surface

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- Figures S1 to S6
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Other supporting materials for this manuscript include the following:

- Movies S1 to S3
Figure S1. Cytoplasm organization in unfertilized sea urchin eggs. (A) Confocal images of an unfertilized sea urchin egg fixed and stained for Microtubules and F-actin. (B) Confocal images of a fertilized sea urchin egg fixed and stained for MTs and F-actin. Images are maximum intensity projections of a mid-slice egg stack. (C, left) Vector field for internal flows in an unfertilized egg overlaid on DIC images. (C, Right) Heat map of the flow speed and streamlines for the same frame as left. Scale bars 30 µm.
Figure S2. Magnetic force calibration. (A) Speed of 1 μm magnetic beads moved in a test viscous fluid, plotted as a function of their distance to the magnet tip, used to calibrate the magnetic gradient and measure the magnetic force applied on single beads. The red curve is a double exponential fit. (B) Magnetic force at 70 μm from the magnet tip, plotted as a function of aggregate size to calibrate how magnetic forces evolve as a function of aggregate size, using a test in vitro viscous fluid. The red curve is a cubic fit. Thin curves indicate 95 percent of confident interval of the fit. (C) (Top) Oil droplet containing hydrophobic beads aggregate injected into the egg. Intensity profile along the two main axes of aggregate inside the oil droplet imaged in bright field. This profile is used to compute the mean size of the aggregate. (Bottom) Hydrophilic beads injected into the cytoplasm. Intensity profile along the two main axes of beads aggregate inside cytoplasm imaged in fluorescence microscopy. This profile is used to compute the mean size of the aggregate. Scale bars, 10 μm.
Figure S3. Comparison of different two- and three-element viscoelastic models to fit cytoplasm rheology. (A) Schematic configurations of dashpots and springs in different viscoelastic models along with the corresponding creep and recovery curves. (B) Scaled creep curve of the oil droplet as in Fig. 3C with the red lines indicating fits of the corresponding viscoelastic models from the top row in A. (C) Normalized recovery curve of the experiment in B fitted with the decay curves of various viscoelastic models. The red line in the Maxwell model is an average of the data values, and not a fit per se.
Figure S4. Impact of osmotic treatments on cell and nuclear size, and flows created by the motion of a small particle. (A) Egg and female nucleus diameter at different osmotic conditions (n=20 cells for each condition). (B) Vector field of cytoplasm flows as a 1 µm bead is pulled through the cell. The moving direction of the bead is indicated by the red arrow. Scale bar, 30 µm. Error bars correspond to the SD of the data.
Figure S5. Validation of finite element 3D hydrodynamic simulations. (A) Normalized simulation output values of the two viscosities and time-scale in the Oldroyd-B model plotted as functions of oil elastic modulus. (B) Displacement curve of pulling and release phase for the same sphere of 20 µm in diameter using different discretization mesh sizes in the simulation. (C, top) Output values of viscosity $\eta_1$ computed from the 3D simulation results using the Jeffreys’ model plotted as a function of the input value given to the simulation. (Middle) Plot of the output/input ratio of the second viscosity $\eta_2$ in the Oldroyd-B model as a function of different input values for $\eta_1$. (Bottom) Plot of the output/input ratio of the time-scale $\tau_2 = \eta_2k$ in the Oldroyd-B model, as a function of different input values for $\eta_1$. (D) Output values of $\eta_2$, output/input ratio for $\eta_1$, and output/input ratio of $\tau_2$ plotted as functions of input values for $\eta_2$. (E) Output values of $\tau_2$, output/input ratio for $\eta_1$, and output/input ratio of $\eta_2$ plotted as functions of input values for $\tau_2$. Dashed red lines guide the eyes and correspond to equal values for input and output. (F) Numerical streamlines and speed heat maps for the same simulation in Fig. 3 and the time point 26 s on the planes perpendicular to the pulling direction.
Figure S6. Initial position of droplets and viscoelastic time-scales at different aspect ratio. (A) Distribution of normalized initial positions of oil droplets in experiments presented in Fig. 4. (B) Viscoelastic time-scale during the pulling phase, and (C) in the releasing phase computed from the simulations as functions of confinement ratio.
| Parameters       | Physical Meanings                      | Values          |
|------------------|----------------------------------------|-----------------|
| $f_0$ [pN]       | Pulling force amplitude                | 20              |
| $t_r$ [s]        | Pulling time                           | 8               |
| $t$ [s]          | Simulation temporal length             | 16/30           |
| $\tau_2$ [s]     | Viscoelastic time-scale                | 33              |
| $\mu_s$ [Pa.s]  | Solvent viscosity                      | 0.795           |
| Viscosity [Pa.s] | Viscosity of the fluid                 | 7.057           |
| E [Pa]           | Young modulus of sphere                | 3.2e5           |
| $\nu$            | Poisson ratio of sphere                | 0.35            |
| $\rho$ [kg/m$^3$]| Density of cytoplasm                   | 1000            |
| $\rho_s$ [kg/m$^3$] | Density of sphere                   | 1190            |
| R [µm]           | Cell radius                            | 50              |
| $r$ [µm]         | Sphere radius                          | [3: 1: 25]      |
| Wall condition   | Boundary condition on the walls        | No slip/Slip    |
| $[x_0, z_0]$ [µm] (Figs. 4A, 5D-F) | Initial position on the plane            | [0, 0]         |
| $[x_0, z_0]$ [µm] (Figs. 6A, B, D) | Initial position on the plane            | [{±35, ±25, ±15, ±5, ±2}, 0] |
| $[x_0, z_0]$ [µm] (Fig. 6A) | Initial position on the plane            | [0, {±35, ±25, ±15, ±5, ±2}] |
| $y_0$ [µm]       | Initial position perpendicular to the plane | 0              |

Table S1. Parameters used in 3D finite-element simulations.
SUPPLEMENTAL MOVIE LEGENDS

Movie S1. Pulling objects at different length scales in the cytoplasm. Time-lapses of pulled objects of diverse sizes using calibrated magnetic forces, directed from right to left in unfertilized sea urchin eggs. Time is in second and the scale bar is 30 microns.

Movie S2. Magnetized oil droplets pulled and recoiled at various crowding conditions of cytoplasm. Time-lapses of eggs at distinct crowding conditions injected with oil droplets containing magnetic beads, pulled with magnetic tweezers, and let to recoil. Time is in second and the scale bar is 30 microns.

Movie S3. Experimental and numerical mapping of cytoplasm flows created by the translation of a large object in cells. The vector field of cytoplasm flows overlaid on experimental images as a large object was moved in the cell. Streamlines and speeds were compared between the experiment and COMSOL simulation with the same parameters as that of the experiment. Time is in second and the scale bar is 30 microns.