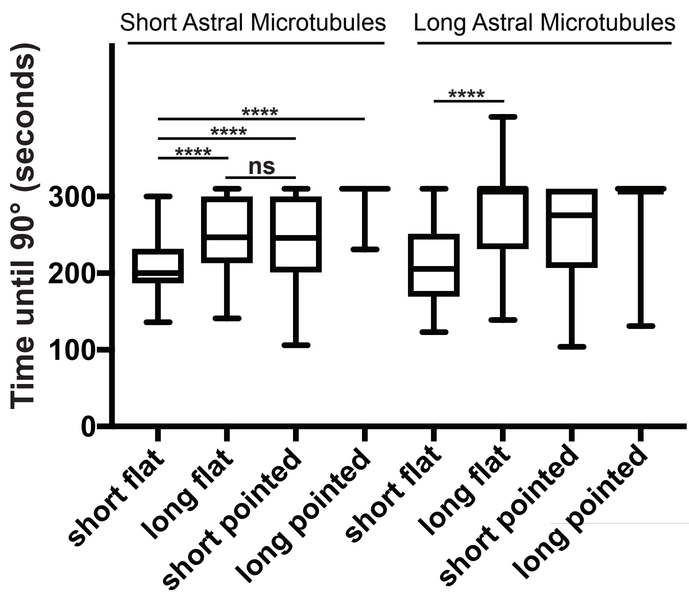


Figure S1. Both short axial ratio and flat spindle poles decrease the time required to rotate to 90° in Cytosim simulations. Spindles that did not rotate to 90° during the 300 sec simulation were assigned a time of 310 sec. n=100 simulations for each of 8 conditions. Boxes extend from the 25th to the 75th percentile.
**** indicates $p<.0001$ by ANOVA.

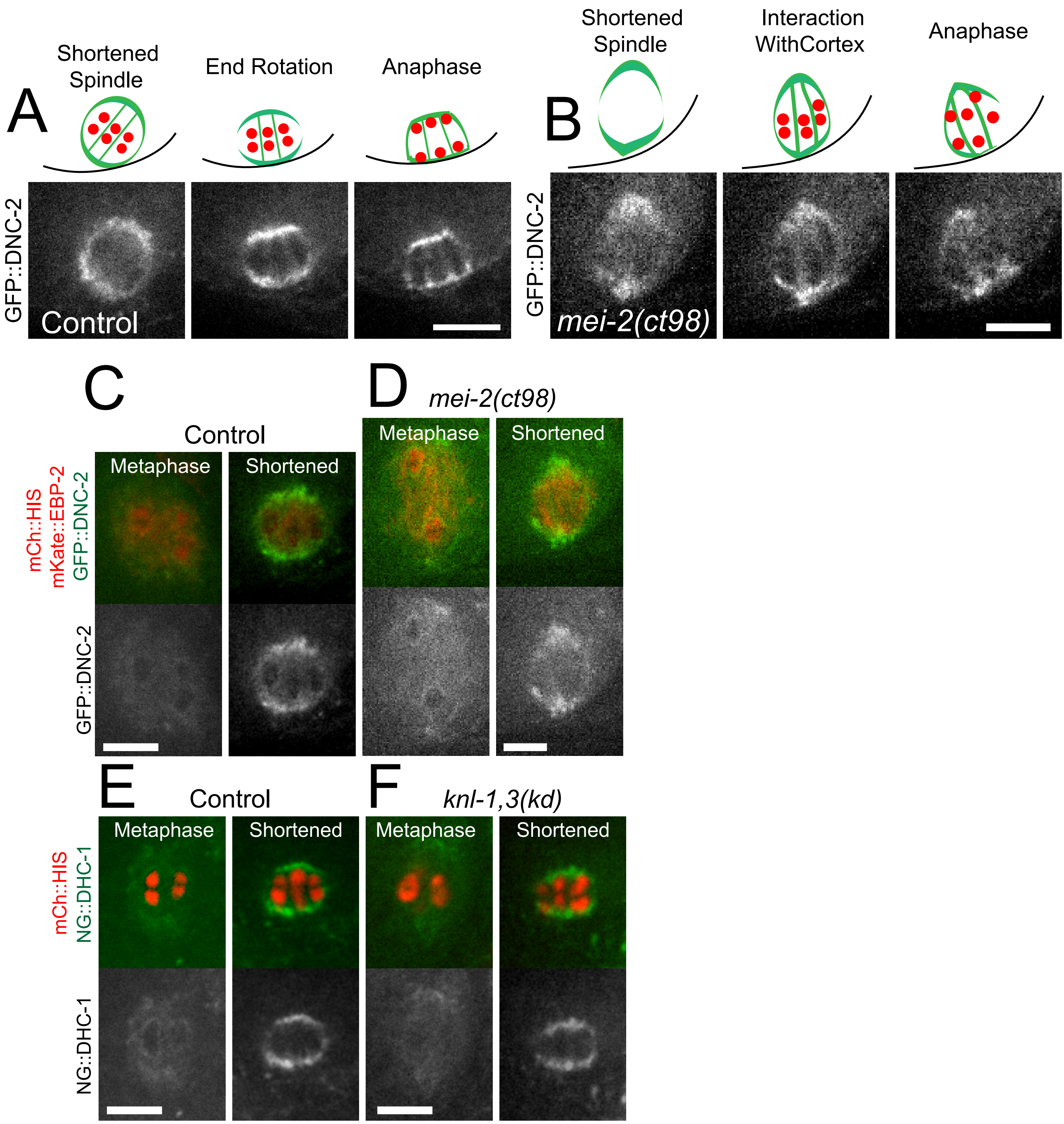


Figure S2. Endogenously tagged dynein regulators label spindle poles in control, *mei-2(ct98)* and *knl-1,3(kd)* embryos. (A-D). GFP::DNC-2 (p50 dynamitin) is present at spindle poles in control (A, C) and *mei-2(ct98)* (B, D) embryos. (E-F). mNeonGree::DHC-1 is present at spindle poles of control (E) and *knl-1,3(kd)* spindles (F).
Bars = 5 μm.

Table S1. *C. elegans* strains.

FM125: *ruIs57[pie-1p::GFP::tubulin + unc-119(+)]V; itIs37[pie-1p::mCherry:H2B::pie-1 3'UTR + unc-119(+)] IV.*

FM13: *mei-2(ct98) I; ruIs57[pie-1p::GFP::tubulin + unc-119(+)]V; itIs37[pie-1p::mCherry:H2B::pie-1 3'UTR + unc-119(+)] IV.*

FM562: *lin-5(he244[egfp::lin-5] II; itIs37[pie-1p::mCherry:H2B::pie-1 3'UTR + unc-119(+)] IV.*

FM582: *mei-2(ct98) I; lin-5(he244[egfp::lin-5] II; itIs37[pie-1p::mCherry:H2B::pie-1 3'UTR + unc-119(+)] IV.*

FM485: *lin-5(he244[egfp::lin-5] II; duSi10[mex-5p::mCherry::H2B operon linker mKate2::PH inserted in K03H6.5] IV.*

FM583: *mei-2(ct98) I; lin-5(he244[egfp::lin-5] II; duSi10[mex-5p::mCherry::H2B operon linker mKate2::PH inserted in K03H6.5] IV.*

FM461: *cpIs54[mex-5p::mKate::PLC(delta)PH(A735T)::tbb-2 3'UTR + unc-119(+)] II; itIs37[pie-1p::mCherry:H2B::pie-1 3'UTR + unc-119(+)] IV; ruIs57[pie-1p::GFP::tubulin + unc-119(+)] V.*

EU1561: *orIs17 [dhc-1::GFP::DHC-1, unc-119(+)]; itIs37 [unc-119(+) pie-1::mCherry::H2B] IV*.

FM460: *prtSi122[pRG629; mex-5p::ebp-2::mKate2::tbb-2 3'UTR + unc-119(+)] II; dnc-2[prt42(N-terminal 3XFLAG::GFP)] III; itIs37[pie-1p::mCherry:H2B::pie-1 3'UTR + unc-119(+)] IV.*

FM462: *mei-2(ct98) I; prtSi122[pRG629; mex-5p::ebp-2::mKate2::tbb-2 3'UTR + unc-119(+)] II; dnc-2[prt42(N-terminal 3XFLAG::GFP)] III; itIs37[pie-1p::mCherry:H2B::pie-1 3'UTR + unc-119(+)] IV.*

HR399: *unc116(f130) unc-36(e251) III*

FM568: *lin-5(cp288[lin-5::mNG-C1^3xFlag]) II; knl-1(lt53[knl-1::GFP::tev::loxP::3xFlag]))III; itIs37 [pie-1p::mCherry::H2B::pie-1 3'UTR + unc-119(+)] IV; knl-3 (lt46 [GFP::knl-3]) V*

FM593: *dhc-1(cp268[dhc::mNG-C1^3xFlag]) I; knl-1(lt53[knl-1::GFP::tev::loxP::3xFlag]))III; itIs37 [pie-1p::mCherry::H2B::pie-1 3'UTR + unc-119(+)] IV; knl-3 (lt46 [GFP::knl-3]) V*

FM553: *cpIs103[Psun-1>TIR1-C1::F2A::mTagBFP2-C1::NLS + SEC] II; knl-1(du5 [KNL-1::AID]) III; itIs37 [pie-1p::mCherry::H2B::pie-1 3'UTR + unc-119(+)] IV; ruIs57 [pie-1p::GFP::tubulin + unc-119(+)] V; knl-3(du2 [AID::KNL-3]) V*

FM554: *ASPM-1(or1935 [GFP::ASPM]) I; cpIs103[Psun-1>TIR1-C1::F2A::mTagBFP2-C1::NLS + SEC] II; knl-1(du5 [KNL-1::AID]) III; itIs37 [pie-1p::mCherry::H2B::pie-1 3'UTR + unc-119(+)] IV; knl-3(du2 [AID::KNL-3]) V*

FM594: dhc-1(cp268[dhc::mNG-C1^3xFlag]) I; itIs37 [pie-1p::mCherry::H2B::pie-1 3'UTR + unc-119(+)] IV

FM595: *lin-5(cp288[lin-5::mNG-C1^3xFlag]) II; itIs37 [pie-1p::mCherry::H2B::pie-1 3'UTR + unc-119(+)] IV*

Supplementary materials and methods

Cytosim code

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% SIM %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

set simul INVIVO          %Parameters that describe the simulation physics
{
   time_step = 0.001      %The time interval, in seconds, that passes between each timepoint calculated by the Langevin
   steric = 1, 100        %Sets whether fibers and solids can sterically repel each other. 1 is a Boolean that sets steric to
                          %TRUE; 100 is the energy cost of violating sterics
   viscosity = 1          %µm²/s; viscosity of the cytoplasm in an oocyte (Daniels et al., 2006)
   tolerance = 0.01       %Describes the precision of object placement calculations (smaller is more precise)
   kT = 0.0042            %pN.µm; thermal energy of the Brownian system, set for 24C
}

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%SPACE %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
set space cell                    %Parameters that describe the simulation space
{
   geometry = ( capsule 5 15 )    %µm; defines the half-lengths of the x and y axes of a capsule object
}

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%FIBERS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

set fiber microtubule
{
   rigidity = 20                  %pN.µm²; related to persistence length (Gittes et al., 1993)
   segmentation = 0.5             %µm; defines the spacing between calculated points on a fiber
   confine = inside, 100          %Sets confinement of fibers to space; number sets energy cost of violating confinement
   steric = 1, 0.05               %Turns sterics on for this fiber; second number is in µm and defines repulsion radius
   activity = dynamic             %Enables fiber dynamics (growth, shrinkage)
   unit_length = 0.01             %µm; defines minimal length of a “monomer” for fiber growth (must be <= growing_speed
   growing_speed = 0.08           %µm/s; defines growth rate of fiber dynamic end
   shrinking_speed = -0.2         %µm/s; defines shrinking rate of fiber dynamic end
   hydrolysis_rate = 0.8, 2       %s⁻¹; frequency of fiber switching to shrinkage on dynamic end
   rescue_rate = 0.01             %s⁻¹; frequency of fiber switching to growth on dynamic end
   growing_force = 1              %pN; characteristic force for polymer assembly
   binding_key  = 1               %Numeric designator that defines which hands and couples can interact/bind
}

set fiber microtubule2
{
   rigidity = 20                  %pN.µm²; related to persistence length (Gittes et al., 1993)
   segmentation = 1               %µm; defines the spacing between calculated points on a fiber
   confine = inside, 100          %Sets confinement of fibers to space; number sets energy cost of violating confinement
   binding_key = 2                %Numeric designator that defines which hands and couples can interact/bind
}

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% HANDS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

set hand nucleator
{
   unbinding_rate = 0             %s⁻¹; frequency of the hand letting go of a fiber if bound
   unbinding_force = 5            %pN; force descriptor for the Kramer’s force-dependent unbinding of the hand
   activity = nucleate            %Sets activity of this hand to generate fibers
   nucleate = 1, microtubule2, ( fiber_length= 0.2 )
   %Defines that this hand will generate a single fiber of type “microtubule2” with an initial length of 0.2 µm.
   display = ( size=2; color= green; )       %Sets display parameters for visualization
}
set hand concrete
{
   binding_rate = 6               %s⁻¹; frequency of the hand binding a nearby fiber
   binding_range = 0.05           %µm; defines minimal distance for hand to be able to bind a fiber
   unbinding_rate = 0             %s⁻¹; frequency of the hand letting go of a fiber if bound
   binding_key = 2                %Numeric designator that defines which hands and couples can interact/bind
```

```
    display = ( size=2; color= purple; )      %Sets display parameters for visualization
}

set hand nucleator2
{
    unbinding_rate = 0              %s-1; frequency of the hand letting go of a fiber if bound
    unbinding_force = 3             %pN; force descriptor for the Kramer's force-dependent unbinding of the hand
    activity = nucleate
    nucleate = 2, microtubule, ( fiber_length= 1.5 )
    %Defines that this hand will generate a single fiber of type "microtubule" with an initial length of 1.5 μm.
    display = ( size=2; color= red; )          %Sets display parameters for visualization
}

set hand cargoD
{
    binding_rate = 2                %s-1; frequency of the hand binding a nearby fiber
    binding_range = 0.1             %μm; defines minimal distance for hand to be able to bind a fiber
    unbinding_rate = 0              %s-1; frequency of the hand letting go of a fiber if bound
    unbinding_force = 6             %pN; force descriptor for the Kramer's force-dependent unbinding of the hand
    binding_key = 2                 %Numeric designator that defines which hands and couples can interact/bind
    display = (size=2; color=0xFF000001)          %Sets display parameters for visualization (color is in HEX)
}

set hand dynein
{
    binding_rate = 0.5              %s-1; frequency of the hand binding a nearby fiber
    binding_range = 0.1             %μm; defines minimal distance for hand to be able to bind a fiber
    unbinding_rate = 0.1            %s-1; frequency of the hand letting go of a fiber if bound
    unbinding_force = 8             %pN; force descriptor for the Kramer's force-dependent unbinding of the hand
    binding_key = 1                 %Numeric designator that defines which hands and couples can interact/bind
    activity = move                 %Sets activity so that this hand can motor on fibers
    max_speed = -0.1                %μm/s; defines maximum translocation (towards the minus end) with no load
    stall_force = 6                 %pN; defines force-load at which motor will stall on a fiber
    binding_key = 1                 %Numeric designator that defines which hands and couples can interact/bind
    display = (size=2; color=0xFF000001)          %Sets display parameters for visualization (color is in HEX)
}

%%%%%%%%%%%%%%%%%%%%%%%%%%%SINGLES %%%%%%%%%%%%%%%%%%%%%%%%%%%

set single spindleNucleator
{
    hand = nucleator2               %Defines the hand on a simple agent
    stiffness = 100                 %pN/μm; used to calculate strain and deformation of single under force
}

set single corticalNucleator
{
    hand = nucleator                %Defines the hand on a simple agent
    activity = fixed                %Sets this single to be fixed in space (does not move with Brownian)
    stiffness = 1000                %pN/μm; used to calculate strain and deformation of single under force
}

set single corticalGlue
{
    hand = concrete                 %Defines the hand on a simple agent
    confine = surface               %Sets this single to be fixed on the edge of the 2D space
    stiffness = 500                 %pN/μm; used to calculate strain and deformation of single under force
}
```

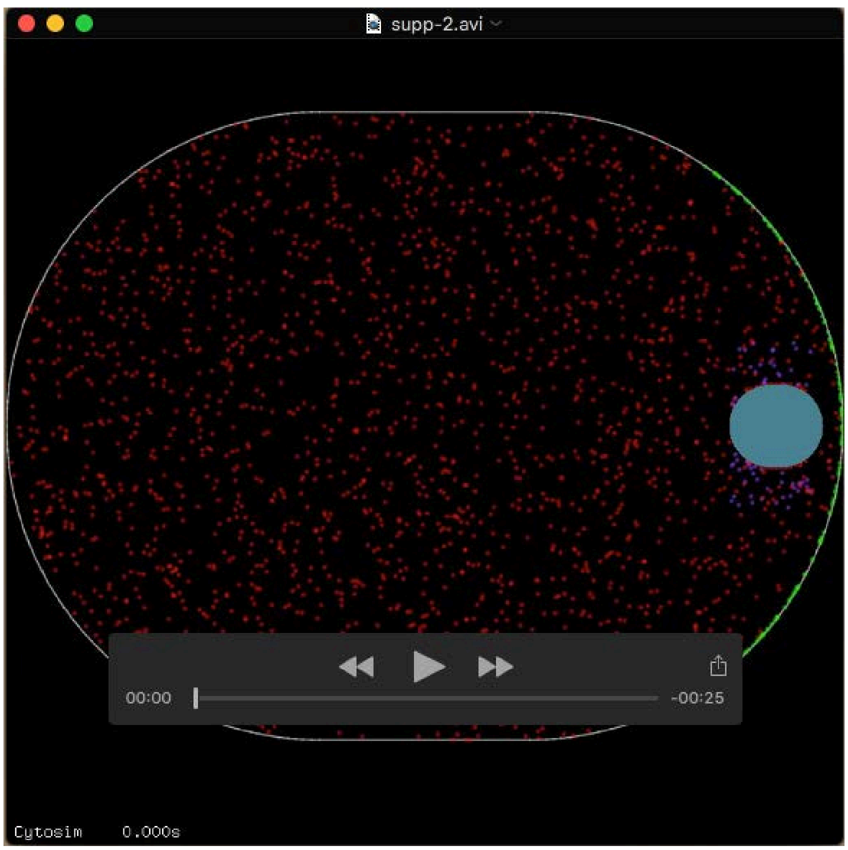
```
%%%%%%%%%%%%%%%%%%%%%%%%%%COUPLES %%%%%%%%%%%%%%%%%%%%%%%%%%

set couple Dynein
{
   hand1 = cargoD               %Defines the hand on an agent that can bind two fibers
   hand2 = dynein               %Defines the hand on an agent that can bind two fibers
   stiffness = 100              %pN/µm; used to calculate strain and deformation of couple under force
   fast_diffusion = 1           %Boolean; if enabled unbound couples are not given explicit positions but are presumed
                                %to diffuse so quickly they can interact with a random fiber at any point.
   length = 0.03                %µm; defines the length of the linker between two hands
   activity = crosslink         %Sets couple to bind fibers with both hands and transmit forces between them
}

%%%%%%%%%%%%%%%%%%%%%%%%%% SOLIDS %%%%%%%%%%%%%%%%%%%%%%%%%%

set solid spindle
{
   confine = all_inside, 100    %Sets solid to be confined inside the space with an energy cost of 100 for violations
   steric = 1                   %Boolean; spindle solids cannot be crossed by other steric components
   display = { style=6 }        % Sets display parameters for visualization
}

new space cell

%%%%%%%%%%%%%%%%%%%%%%%%%%%% RUN %%%%%%%%%%%%%%%%%%%%%%%%%%%%

new 1 solid spindle             %Generates a solid consisting of many points, some of which are beads and some of
                                %which are nucleators that generate spindle pole microtubules. This code generates one
                                %specific spindle geometry. Several others were also run to compare different spindles.
                                %first three numbers define placement (X,Y,Z) relative to the central coordinates of the
                                %solid at any given timepoint.
{
   nb_points = 34                                         %Sets number of points that make up the solid
   point0 = 0   1.2  0, 0.6                               %Defines a bead of radius 0.6 µm
   point1 = 0   -1.2  0, 0.6                              %Defines a bead of radius 0.6 µm
   point2 = 0.6   0  0, 1.4                               %Defines a bead of radius 1.4 µm
   point3 = -0.6  0  0, 1.4                               %Defines a bead of radius 1.4 µm
   point4 = 1.625 1.06 0  , 0, spindleNucleator           %Defines a nucleator on the spindle pole
   point5 = 1.393 1.174 0  , 0, spindleNucleator          %Defines a nucleator on the spindle pole
   point6 = 1.161 1.289 0  , 0, spindleNucleator          %Defines a nucleator on the spindle pole
   point7 = 0.929 1.403 0  , 0, spindleNucleator          %Defines a nucleator on the spindle pole
   point8 = 0.696 1.517 0  , 0, spindleNucleator          %Defines a nucleator on the spindle pole
   point9 = 0.464 1.631 0  , 0, spindleNucleator          %Defines a nucleator on the spindle pole
   point10 = 0.232 1.746 0  , 0, spindleNucleator         %Defines a nucleator on the spindle pole
   point11 = 0 1.86 0  , 0, spindleNucleator              %Defines a nucleator on the spindle pole
   point12 = -0.232 1.746 0  , 0, spindleNucleator        %Defines a nucleator on the spindle pole
   point13 = -0.464 1.631 0  , 0, spindleNucleator        %Defines a nucleator on the spindle pole
   point14 = -0.696 1.517 0  , 0, spindleNucleator        %Defines a nucleator on the spindle pole
   point15 = -0.929 1.403 0  , 0, spindleNucleator        %Defines a nucleator on the spindle pole
   point16 = -1.161 1.289 0  ,   0, spindleNucleator      %Defines a nucleator on the spindle pole
   point17 = -1.393 1.174 0  , 0, spindleNucleator        %Defines a nucleator on the spindle pole
   point18 = -1.625 1.06 0  , 0, spindleNucleator         %Defines a nucleator on the spindle pole
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   point19 = 1.625 -1.06 0  , 0, spindleNucleator         %Defines a nucleator on the spindle pole
   point20 = 1.393 -1.174 0  , 0, spindleNucleator        %Defines a nucleator on the spindle pole
   point21 = 1.161 -1.289 0  , 0, spindleNucleator        %Defines a nucleator on the spindle pole
   point22 = 0.929 -1.403 0  , 0, spindleNucleator        %Defines a nucleator on the spindle pole
   point23 = 0.696 -1.517 0  , 0, spindleNucleator        %Defines a nucleator on the spindle pole
   point24 = 0.464 -1.631 0  , 0, spindleNucleator        %Defines a nucleator on the spindle pole
   point25 = 0.232 -1.746 0  , 0, spindleNucleator        %Defines a nucleator on the spindle pole
   point26 = 0 -1.86 0  , 0, spindleNucleator             %Defines a nucleator on the spindle pole
   point27 = -0.232 -1.746 0  , 0, spindleNucleator       %Defines a nucleator on the spindle pole
```

```
    point28 = -0.464 -1.631 0  , 0, spindleNucleator      %Defines a nucleator on the spindle pole
    point29 = -0.696 -1.517 0  , 0, spindleNucleator      %Defines a nucleator on the spindle pole
    point30 = -0.929 -1.403 0  , 0, spindleNucleator      %Defines a nucleator on the spindle pole
    point31 = -1.161 -1.289 0  , 0, spindleNucleator      %Defines a nucleator on the spindle pole
    point32 = -1.393 -1.174 0  , 0, spindleNucleator      %Defines a nucleator on the spindle pole
    point33 = -1.625 -1.06 0  , 0, spindleNucleator       %Defines a nucleator on the spindle pole

   position = 16.8 0 0 at 0 0                             %Places the solid in absolute space
   orientation = 1 0 0                                    %Aligns the spindle solid to the X axis
}

new 2000 couple Dynein                                    %Places 2000 couples randomly in the space
new 100 single corticalGlue                               %Places 100 singles
{
    position = rectangle 2 4 at 16.5 0                    %Places these singles in a rectangle centered at 16.5 in X
}

new 140 single corticalNucleator                          %Places 140 singles
{
    position = arc 30 2.0 at 19.96 0                      Places them in an arc at 19.96 in X with radius 30 and width 2
}

run simul *                                               %Run the simulation
{
    nb_steps = 3000                                       %Number of calculated timepoints
    nb_frames = 3                                         %Number of frames generated for visualization
}

change single corticalNucleator {activity = fixed;}       %Changes single so that they cannot move anymore


run simul *                                               %Run the simulation
{
    nb_steps = 300000                                     %Number of calculated timepoints
    nb_frames = 300                                       %Number of frames generated for visualization
}
```

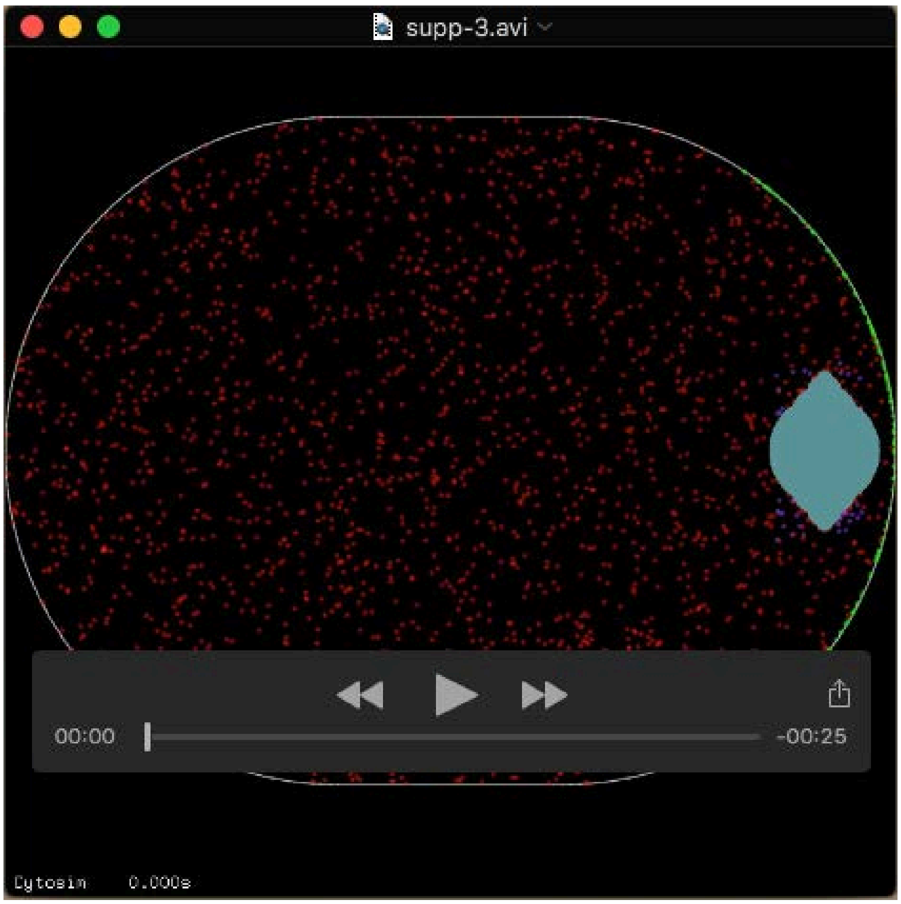
Development • Supplementary information

Movies

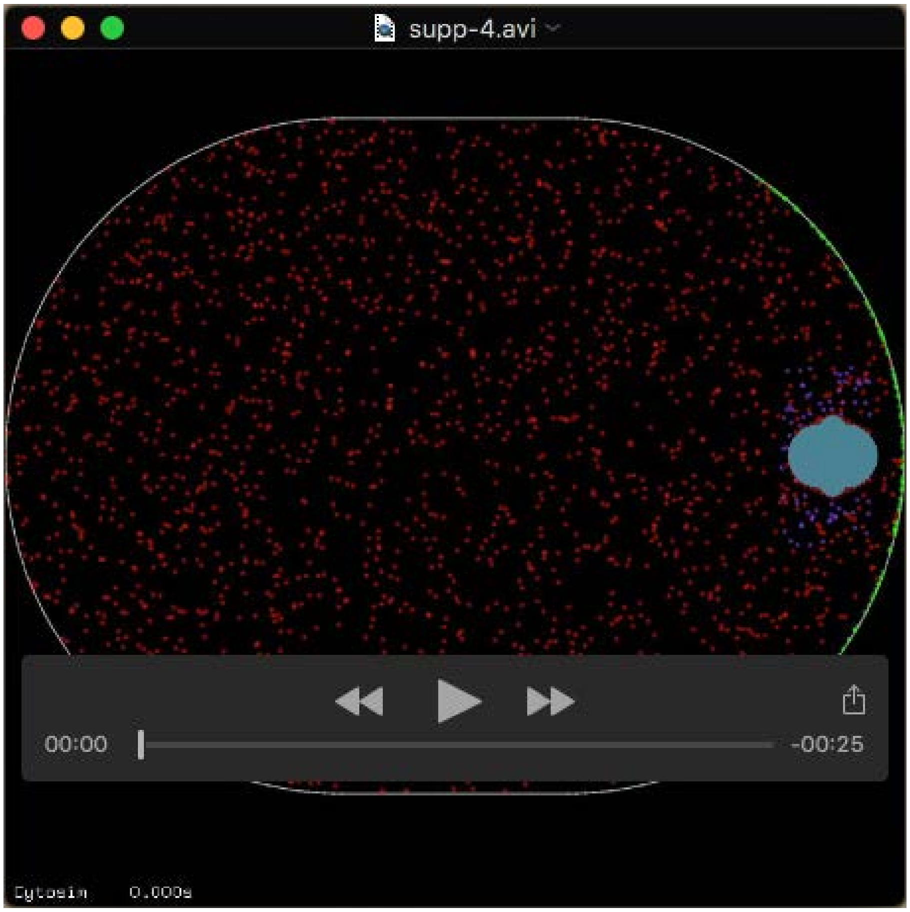
For all movies: Red dots represent cytoplasmic dynein molecules that associate randomly with astral or cortical microtubules, motor to the minus end, and dissociate with a rate constant that increases with applied force. Pulling toward the cortex occurs transiently when a dynein contacts both a cortical microtubule and an astral microtubule. After the first frame, only dynein molecules engaged with a microtubule are displayed. Astral microtubules emanate from nucleators arranged to mimic the localization of dynein/LIN-5 on control (flat) or *mei-2(ct98)* (pointed) poles. Green dots represent nucleation sites for short cortical microtubules. Purple dots represent a "cortical glue" that resists detachment once close contact between the pole and cortex is achieved. All spindles start at a fixed distance from the cortex and perfectly parallel to the cortex.



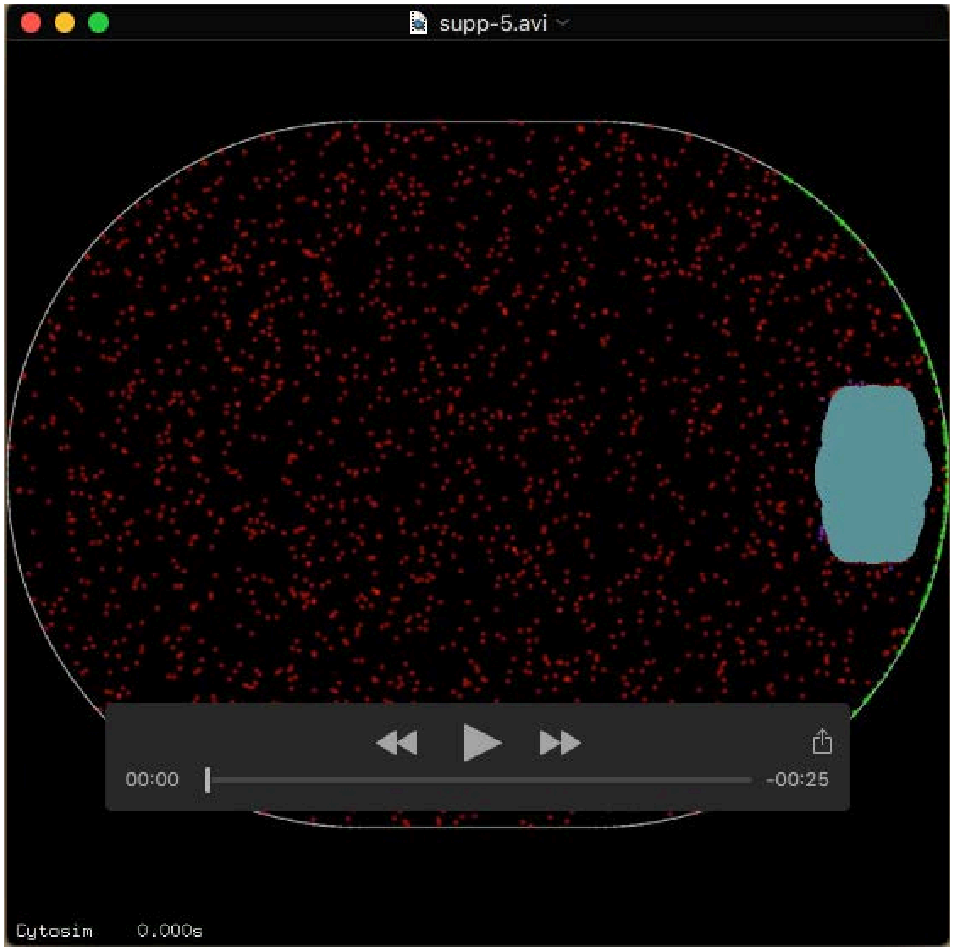
Movie 1. Simulation of rotation of a short (0.9 axial ratio) spindle with flattened poles and short astral microtubules. This shape mimics control spindles midway through rotation. Astral microtubules are short due to a polymerization rate of 0.06 μm/s.



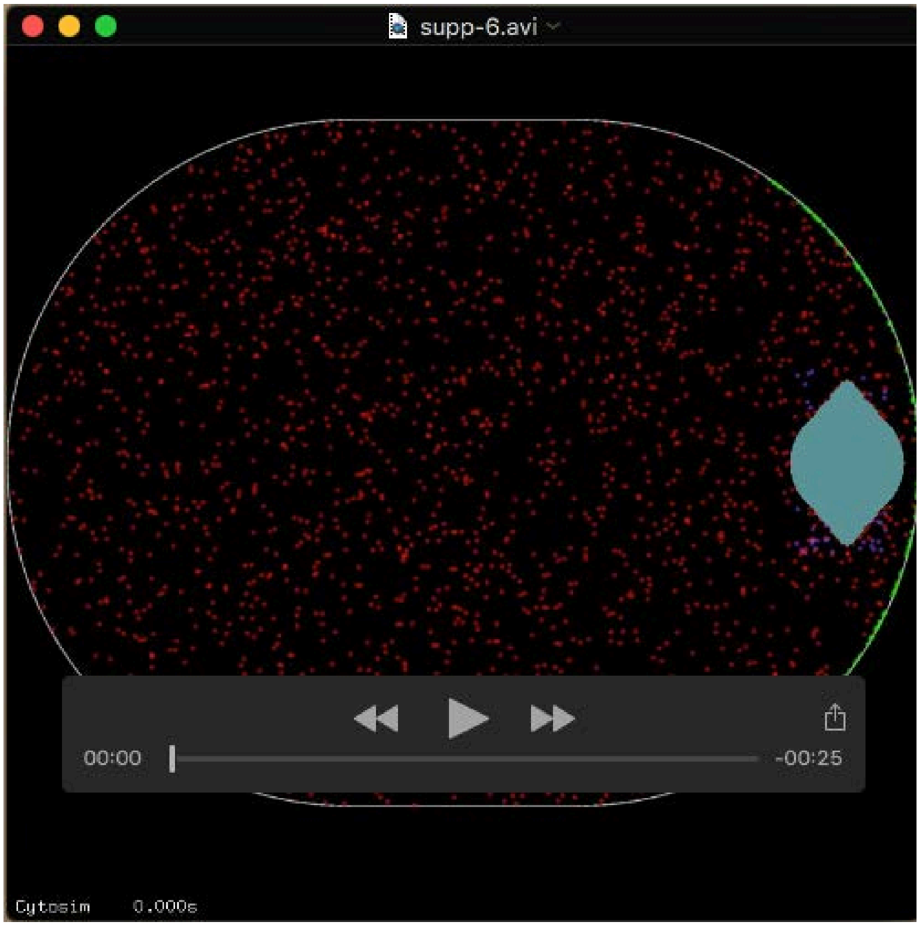
Movie 2. Simulation of rotation of a long (1.5 axial ratio) spindle with pointed poles and short astral microtubules. This shape mimics the shape of the shortest mei-2(ct98) spindles that rotate partially to a diagonal angle relative to the cortex. Astral microtubules are short due to a polymerization rate of 0.06 μm/s.



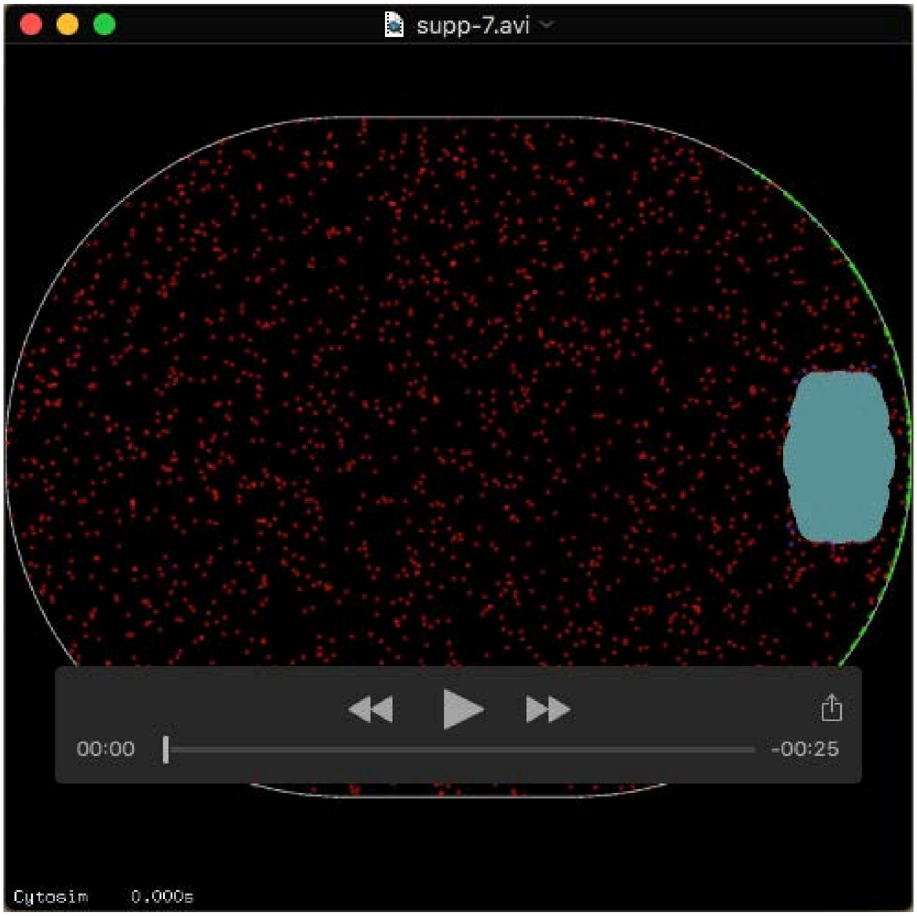
Movie 3. Simulation of rotation of a short (0.9 axial ratio) spindle with pointed poles and short astral microtubules. This spindle has the axial ratio of a control spindle and pointed poles like a *mei-2(ct98)* spindle. Astral microtubules are short due to a polymerization rate of 0.06 μm/s.



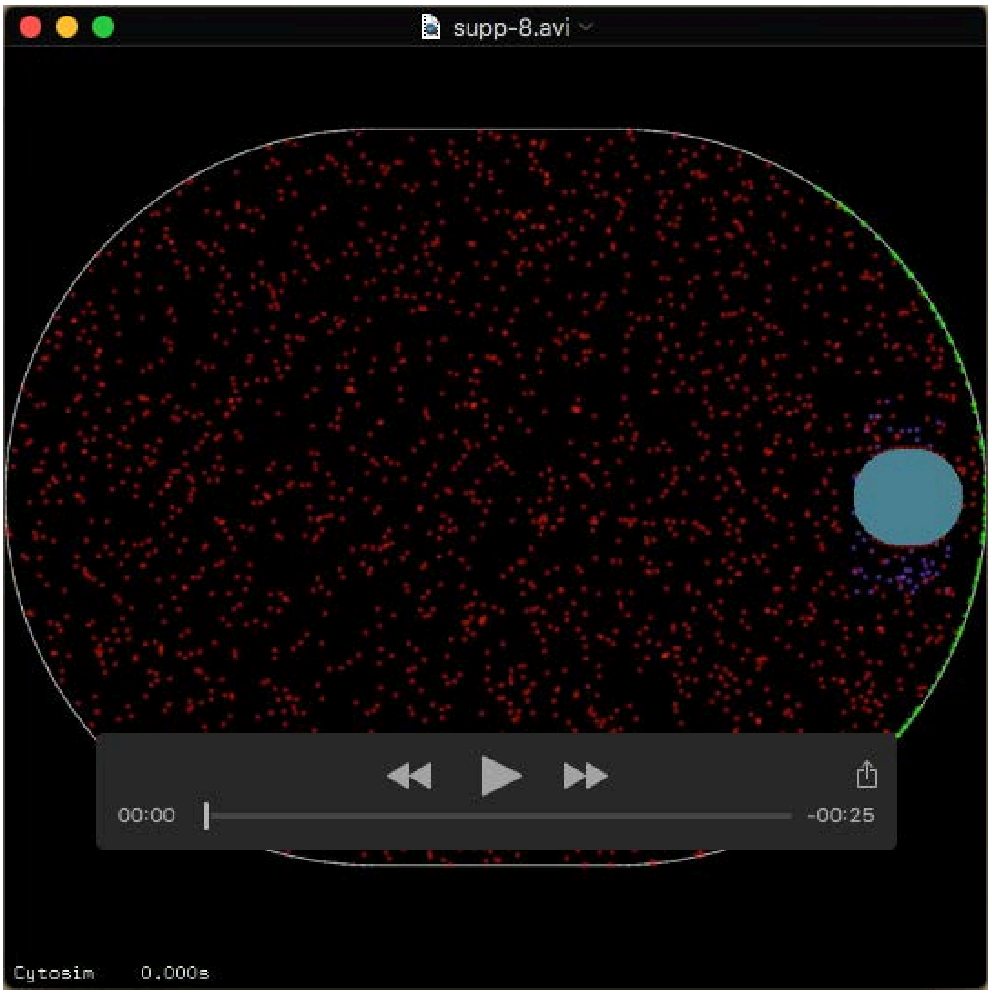
Movie 4. Simulation of rotation of a long (1.5 axial ratio) spindle with flattened poles and short astral microtubules. This spindle has the axial ratio of the shortest *mei-2(ct98)* spindles that rotate partially to a diagonal angle relative to the cortex but with poles shaped like those of a control spindle. This shape is also similar to that of *knl-1,3(kd)* spindles that partially rotate or fail to rotate. Astral microtubules are short due to a polymerization rate of 0.06 μm/s.



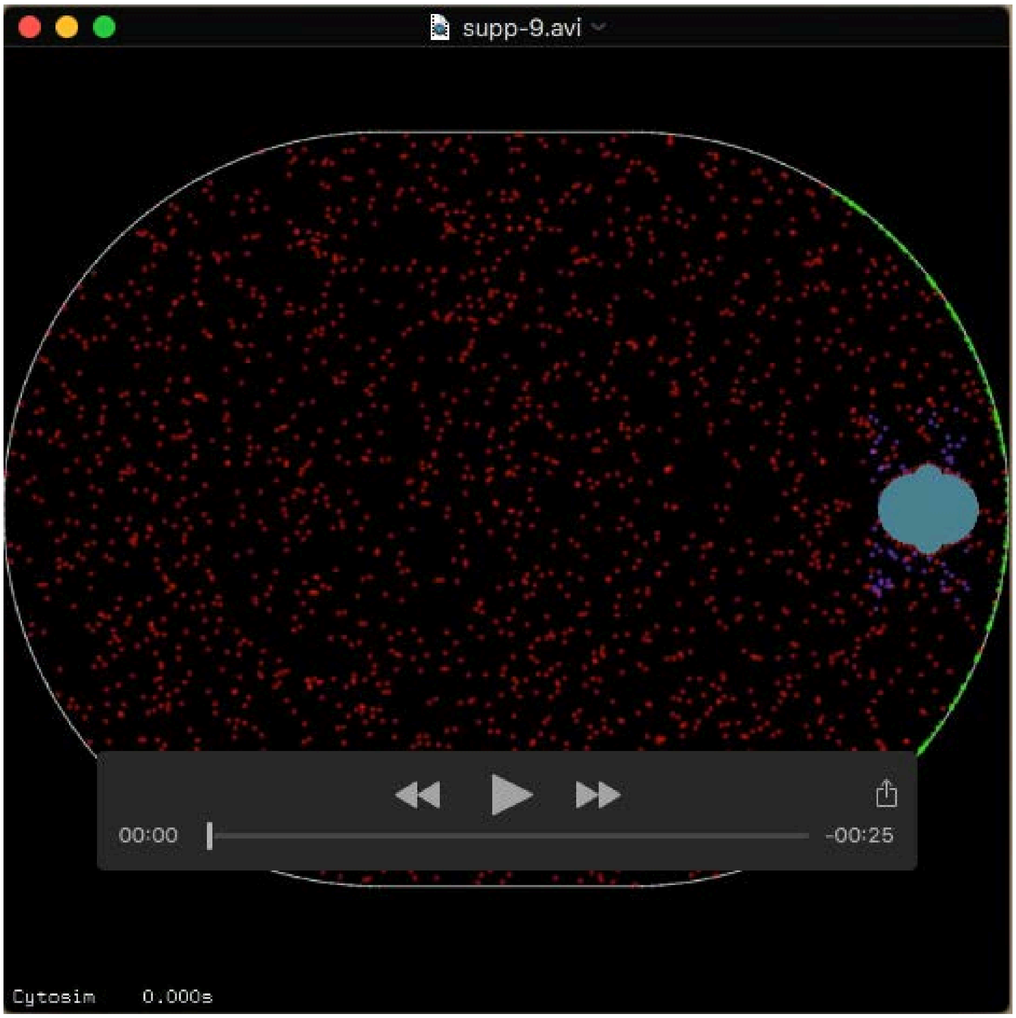
Movie 5. Simulation of rotation of a long (1.5 axial ratio) spindle with pointed poles and long astral microtubules. This shape mimics the shape of the shortest *mei-2(ct98)* spindles that rotate partially to a diagonal angle relative to the cortex. Astral microtubules are long due to a polymerization rate of 0.18 μm/s.



Movie 6. Simulation of rotation of a long (1.5 axial ratio) spindle with flattened poles and long astral microtubules. This spindle has the axial ratio of the shortest *mei-2(ct98)* spindles that rotate partially to a diagonal angle relative to the cortex but with poles shaped like those of a control spindle. This shape is also similar to that of *knl-1,3(kd)* spindles that partially rotate or fail to rotate. Astral microtubules are long due to a polymerization rate of 0.18 μm/s.



Movie 7. Simulation of rotation of a short (0.9 axial ratio) spindle with flattened poles and long astral microtubules. This shape mimics control spindles midway through rotation. Astral microtubules are long due to a polymerization rate of 0.18 μm/s.



Movie 8. Simulation of rotation of a short (0.9 axial ratio) spindle with pointed poles and long astral microtubules. This spindle has the axial ratio of a control spindle and pointed poles like a *mei-2(ct98)* spindle. Astral microtubules are long due to a polymerization rate of 0.18 μm/s.