Mechano-logical Model of *C. elegans* Germ Line Suggests Feedback on the Cell Cycle

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Summary

The *C. elegans* germ line is an outstanding model system to study the control of cell division and differentiation. While many of the molecules that regulate germ cell proliferation and fate decisions have been identified, how these signals interact with cellular dynamics and physical forces within the gonad remains poorly understood. We therefore developed a dynamic, 3D *in silico* model of the *C. elegans* germ line, incorporating both the mechanical interactions between cells and the decision-making processes within cells. Our model successfully reproduces key features of the germ line during development and adulthood, including a reasonable ovulation rate, correct sperm count, and appropriate organization of the germ line into stably maintained zones. The model highlights a previously overlooked way in which germ cell pressure may influence gonadogenesis, and also predicts that adult germ cells may be subject to mechanical feedback on the cell cycle akin to contact inhibition. We provide experimental data consistent with the latter hypothesis. Finally, we present cell trajectories and ancestry recorded over the course of a simulation. The novel approaches and software described here link mechanics and cellular decision-making, and are applicable to modeling other developmental and stem cell systems.
Introduction

Controlled cell proliferation and fate decisions underlie development, tissue maintenance, regeneration and repair. While tremendous progress has been made identifying the molecular pathways that regulate division and differentiation in individual cells, less is known about how the behavior of cell populations is coordinated within a developing organ. During organogenesis, cells are influenced by a complex interplay between intrinsic molecular processes, external signals and mechanical forces. Unraveling the contribution of each component is experimentally challenging.

Here, we present a computational model of *C. elegans* germ line development and maintenance, a practical experimental system. Hermaphrodite gonadogenesis is summarized in Fig. 1, and takes place primarily over the larval life cycle stages L1-L4 (Fig. 1A). Our simulations begin immediately after the establishment of two separate gonad arms at the end of L2 (see Fig. 1B). A Distal Tip Cell (DTC), positioned at the end of each gonad arm, performs leader cell and signaling roles, both during gonadogenesis and in adulthood (Kimble and Hirsh, 1979; Kimble and White, 1981).
Fig. 1. *C. elegans* germ line development and organization. (A) The *C. elegans* life cycle. Larval development is subdivided into four stages; at each stage the growing gonad is indicated in grey (not to scale). (B) A cartoon of germ line development within the gonad (not to scale, underrepresented cell counts from L2 onwards). The DTCs and somatic gonadal tissues are pale blue, with the central oval representing multiple cells and sheath cells omitted. Germ cells are color coded as follows: proliferating and meiotic S cells are yellow, meiotic cells are green, sperm dark blue, and oocytes pink. (C) A cartoon depicting germ cell connections to the rachis. (D) Micrograph of a single early adult gonad arm, for comparison with drawings. The gonad arm and proximal-most oocyte are outlined. When the first oocyte is ovulated, sperm are pushed into the spermatheca. Scale bar 25 µm, composite of a distal and a proximal image.
During the L3 and L4 larval stages germ cells rapidly divide. The pressure generated by these divisions contributes to the anterior-posterior growth of the organ, as does active DTC migration (Kimble and White, 1981; Killian and Hubbard, 2005). As the DTCs move further from the center of the animal, proximal germ cells go out of range of their proliferation-promoting/differentiation-inhibiting signal and enter meiosis (green cells, Fig. 1B). During L4, the proximal-most meiotic cells differentiate as spermatocytes, each producing four sperm. In adults, oogenic germ cells either undergo apoptosis in the turn or develop into oocytes (Gumienny et al., 1999). With the exception of spermatogonia, sperm and the proximal-most oocytes, “germ cells” are technically syncytial, since they retain a small opening onto the rachis, a central cytoplasmic reservoir that streams material into maturing oocytes (Fig. 1C) (Wolke et al., 2007). However, since germ nuclei are surrounded by their own cytoplasm and do not appear to share cytoplasmic components, they are referred to as “germ cells” (Hirsh et al., 1976).

Germ cells are prevented from entering prophase of meiosis I within the first ~13 cell diameters (CD) of the DTC in L3 larvae (20-25CD in adults) (Hansen et al., 2004). The DTC expresses at least two membrane bound DSL family ligands, LAG-2 and APX-1, which activate the GLP-1 (Notch family) receptor on nearby germ cells. Downstream, GLP-1 acts via LAG-1 to inhibit the accumulation of specific RNA-binding proteins, preventing meiotic entry (reviewed in Hansen and Schedl, 2013; Kershner et al., 2013).

Many system-level questions about the germ line remain unanswered. For example, what is the precise interplay between GLP-1 activity, cell cycle and meiotic entry? What are the properties of the germ cell cycle, and how do these alter with age and environmental conditions? Given that the two known DTC-expressed ligands are membrane bound, what determines when and where a germ cell enters meiosis? How does gonad structure affect germ cells, and how do germ cells, in turn, influence gonadogenesis? In silico models provide a complementary approach to laboratory experiments for investigating these questions.

Several previous models of the C. elegans germ line have been published. Setty et al. (2012) presented a 2D model of a lengthwise section through the adult gonad, with germ
cells represented by circles restricted to an underlying lattice. The behavior of each germ cell in response to stimuli was modeled using a statechart – a visual formalism similar to a state machine or flowchart that specifies (i) the possible states of a cell, (ii) the allowed transitions between states and (iii) the conditions under which these occur (Harel, 1987). The Setty et al. model accurately reproduced mutant phenotypes and provided predictions concerning proliferative zone stability that were experimentally validated. Beyer et al. (2012) modeled a similar 2D section through the adult gonad using off-lattice cell mechanics. Off-lattice models have no underlying grid, and cells are allowed to move freely in space according to the force applied by their neighbors.

Here we present a combined “mechano-logical” model of the germ line that incorporates new in vivo measurements and extends previous work in important ways. First, our approach combines a statechart description of germ cell behavior with 3D cell mechanics. Second, we take into account the rachis. Third, we cover both larval development and adult homeostasis in a single simulation. We found that introducing two new hypotheses into the model greatly facilitated agreement with experimental measurements. The first was gonadal “stretching” during the late L4. The second was mechanical feedback on adult germ cell proliferation akin to contact inhibition. We examined a scenario in which distal cells become more tightly packed, and obtained results consistent with a contact inhibition mechanism in vivo. Finally, we incorporated the means to perform cell tracking and clonal labeling in silico, to facilitate interpretation of future experimental results.
Results

Model overview

We begin by summarizing the model (see materials and methods and supplementary materials and methods for further details).

The germ line was simulated using off-lattice mechanics, such that cells move freely under the influence of applied forces rather than being confined to boxes in an underlying grid. Individual germ cells were modeled as spheres, with a repulsion force exerted whenever two cells overlap (Fig. 2A). The approach is similar to (Dunn et al., 2013); see also supplementary materials and methods. We used an existing modeling library, Chaste (Cancer Heart and Soft Tissue Environment) (Mirams et al., 2013), to which was added new code to model the growing gonad and to allow the use of statecharts. Code for both new features is freely available under an open source license (see materials and methods).
Fig. 2. The computational model. (A) Cell mechanics. Overlapping cells experience a repulsion force, and the net force on a cell along with its drag coefficient determines movement at each time step. (B) Growth of the gonad boundary. The DTC (blue) migrates in a U-shape, turning at a prescribed time. The boundary at time $t$ consists of all points a distance $r(t)$ from the DTC path, where $r(t)$ is the gonad radius. Germ cells are restricted to this domain. The model simulates a single gonad arm; the other arm is outlined in grey. (C) The statechart governing germ cell behavior. Dotted lines separate the orthogonal regions of the chart, which deal with different processes and update simultaneously. Each box represents a cell state and arrows indicate the allowed transitions between them. Alongside each transition in square brackets is the condition for it to occur. Red states are initially active in cells at the start of the simulation. Mitosis has no initial state, since cells begin the simulation in a randomly chosen cell cycle phase. Daughter cells inherit their parent’s state upon division. Blue text indicates actions that occur on transition or while in a certain state. The biological hypotheses this statechart represents are discussed in the text.
We simulated a single gonad arm, since both arms are symmetric. Germ cells were confined by a “boundary condition”: a surface representing the gonad membrane that cells cannot cross. The boundary is tube-shaped and was updated over time, forming along the path of the DTC. The DTC itself was explicitly modeled and migrated along a prescribed path over the course of the simulation (Fig. 2B). To ensure continued contact between proliferating germ cells and the migrating DTC (Starich et al., 2014), the DTC makes migratory progress only when germ cells abut the DTC. If DTC migration outpaced germ cell proliferation by one cell diameter (a situation that was minimized by our choice of larval proliferation rate) DTC migration paused temporarily. Our strategy of linking boundary growth to the DTC path allows changes in DTC migration to affect gonad morphology. For instance, if DTC migration is delayed during L3 due to inadequate germ cell proliferation, the turn still occurs at the same prescribed time in the simulation, but closer to the center of the animal, consistent with experimental observations (e.g., Austin and Kimble, 1987; Killian and Hubbard, 2004).

To determine the proper gonad size and growth rate, measurements were obtained from micrographs of larvae at various stages of development. The measured animals were grown at 20°C with abundant food; these are the conditions our model aims to reflect. A target DTC migration rate was calculated for each simulation stage (Fig. S1). The same measurements also revealed that the proximal gonad lengthens significantly during L4, growth that cannot be captured by moving the DTC alone. This gonad “stretching” (discussed below) was included in the model by gradually moving the boundary turn away from the center of the animal in late L4. Finally, the rachis was taken into account by forcing cells distal to and within the turn to lie just inside the boundary edge, creating a space corresponding to the rachis in the center of the arm. Gonad diameter increased appropriately over time, based on our measurements.

A statechart associated with each cell controlled fate decisions and cell cycle progression (see Fig. 2C and supplementary materials and methods). Statecharts are a visual method for specifying the behavior of complex systems (Harel, 1987). Similar to a set of multilayered flowcharts, they contain states (boxes) that can be either active or inactive. Transitions (arrows) dictate how the currently active state is allowed to change. Next to
each transition is a condition (in square brackets) that must be met for it to occur.

At the start of the simulation, 16 germ cells are present and their active states are those outlined in red in Figure 2C. At each subsequent time step, the statechart is checked to see whether conditions exist allowing a transition out of any current state. If so, that transition happens immediately and the state changes. Transition conditions may include dependencies, allowing state changes in response to a cell’s position in the gonad or the time post-hatching. When a cell divides, it inherits its parent’s state. See Supplemental Movie S1 and materials and methods for further details on model progression.

Our statechart incorporates several hypotheses about how germ cells react to their environment. First, cells born sufficiently close the DTC are proliferative, and they and their daughter cells may not enter meiosis within 70 μm (~13 cell diameters) of the distal tip. Beyond this point, cells irreversibly enter meiosis at the earliest opportunity, within the cell cycle constraints described below. 70 μm is around the distance at which initial meiotic entry occurs in the mid-L3, therefore this approach represents a simple spatial threshold model of DTC signaling. We further specified that commitment to meiotic entry must occur during G1; otherwise germ cells undergo one further division. Recent studies, the results of which were not available during our model building, demonstrate experimental support for a very similar general mechanism (Fox and Schedl, 2015). Fox and Schedl (2015) show that cells in mitotic S or G2 complete one final round of division before entering meiosis, indicating that the meiotic entry decision must occur before pre-meiotic S phase. Since G1 is very short in this system, these results further imply that the decision to enter meiosis occurs in the previous cell cycle. However, the experimental results do not preclude the possibility that the meiotic entry decision occurs during the very short G1 of the same cell cycle, as we have modeled here. Nevertheless, consistent with the results of Fox and Schedl (2015), the mechanism modeled here links the meiotic entry decision to GLP-1 activity and to the cell cycle, such that cells experiencing low GLP-1 activity divide once, then enter meiosis. The only exception would be very rare cases where a cell is in the short G1 exactly when GLP-1 activity drops, in which case the cell would enter meiosis from G1 without an intervening division.
The sperm/oocyte decision is simply triggered by distance from the DTC (200µm). Cells arriving at this position before a threshold time become sperm-fated, while cells reaching it later are oocyte-fated. Finally, for reasons discussed below, mechanical feedback akin to contact inhibition was included in the cell cycle model of adult germ cells. This feedback was applied by transiently arresting progress through the cell cycle in cells compressed to less than 70% of their rest volume (see supplementary materials and methods). The remainder of the results section explores the impact these hypotheses had on the simulated germ line.

**Reproducing essential features of germ line development**

Using the parameter set in Table S1, our simulations qualitatively resemble the wild-type germ line throughout development and into adulthood. Figure 3 shows a series of simulation snapshots captured at key points (see also Movie S1 and Table S2). They show that the model reproduced the overall structure of the germ line: a proliferative zone was established, meiotic cells appeared at the appropriate time, sperm and oocytes were produced in roughly correct numbers, and the organization of the germ line was stably maintained for several days. Importantly, we were able to achieve these results using biologically reasonable parameters and gonad dimensions, and without biasing cell movement vis-à-vis the DTC as in previous work (Setty et al., 2012). Notably, the direction of germ cell movement naturally reversed in the simulation after DTC migration was complete.
Fig. 3. Germline simulation snapshots, captured throughout larval development and at two adult time points. In this simulation, germ cells in the Mitosis and MeioticS states are represented in yellow, while cells in Prophase of Meiosis I are green. Total cell counts for this particular simulation are provided in Table S2. Oogenic and spermatogenic cells are represented in red and pale blue respectively, and mature sperm are dark blue. The DTC nucleus, where visible, is cyan. A proportion of oogenic cells undergo programmed cell death (not visible in these snapshots). Parameters as in Table S1, see also Movie S1.
We fit simulation output to quantitative experimental data across a range of properties (Fig. 4). Parameters that could not be determined from the prior literature or from our own measurements are indicated by * in Table S1 and were varied during fitting within estimated feasible ranges. In general, a good agreement was achieved between simulated and expected cell counts during development (Figs. 4A-C). The counts of total cells, proliferative cells, and sperm all increased appropriately, and proliferative cell numbers were stably maintained in the adult (we did not attempt to capture the effects of ageing; Qin and Hubbard, 2015). Moreover, a steady ovulation rate was established, indicated by a falling sperm count (Fig. 4C). The length of the simulated gonad over time also matched the expected growth curve (Fig. 4D). This need not have been the case, because DTC movement can be delayed in our model if germ cells numbers are insufficient to support migration. The implication is that the rate of germ cell proliferation used here (a cycle length of 3 hr in larvae and 8 hr in adults) is reasonable to support normal gonadogenesis. The exact length of the germ cell cycle has been controversial in the field (Kipreos et al., 1996; Crittenden et al., 2006; Fox et al., 2011; Fox and Schedl, 2015).
Fig. 4. Comparing simulated and observed values for various germline properties. Experimental measurements are plotted alongside simulated values for several properties. In each graph, a solid black line gives the simulated result (mean of 30 runs with a region ±1 s.d. shaded), while red lines represent experimental data. Solid red lines correspond to time series and dashed lines to a single value found in the literature. Three vertical dotted lines mark the beginning of L3, L4 and adulthood. Finally, a light grey bar indicates the period where our model switches from larval to adult behavior and parameters. (A-C) Counts of total germ cells, proliferative cells and sperm, respectively, over time in hours post-hatch (hph). (D) Total length of the gonad arm in microns (µm). (E) Distance in cell diameters (CD) to the distal-most row containing 2 or more meiotic cells. (F) Distance in CD to the proximal-most row containing a proliferative cell. Experimental data taken from (Killian and Hubbard, 2005; Hansen et al., 2004; McCarter et al., 1999) and our own measurements, including those used to generate the animation by Stupay and Hubbard on Wormatlas (http://www.wormatlas.org/hermaphrodite/germ%20line/Germframeset.html).
There is also a reasonable fit for the length of the “proliferative zone” in CD from the DTC – an estimate of the size of the stem/progenitor pool. The field defines the proliferative zone or mitotic region as the area distal to the first row containing two or more meiotic cells (Fig. 4E). We also benchmarked the proximal-most row containing a non-meiotic cell (Fig. 4F). Both properties are close on average to the expected values for the young adult. In addition, Figure S2 compares simulated and experimental proliferative zone lengths in microns. While the fit could perhaps be improved further with fine parameter adjustments, the current fit was considered sufficient to begin investigating overall behavior.

**Gonadal stretching during late L4 likely contributes to gonad morphogenesis**

Organ growth is influenced by multiple factors and determining their relative contribution is experimentally challenging. Two independent factors contribute to gonad growth in *C. elegans*: DTC migration and the force generated by germ cell proliferation (Kimble and White, 1981; Killian and Hubbard, 2005). Previous studies have associated the force generated by germ cells with anterior-posterior extension of the gonad arms during L2 and L3.

Our experimental measurements highlighted an additional feature of larval gonadal growth. The proximal region of the gonad arm doubles in length during late L4, as the turn moves away from the center of the animal (Table 1, proximal region data). We specified this stretching in our model (Movie S1). Centrifugal growth of the proximal gonad over this period is difficult to attribute to DTC movement. To investigate whether a reasonably-sized gonad could be produced by DTC migration alone, we ran a simulation with proximal stretching disabled. We calculated that without stretching, the DTC must travel at 46μm/hr during late L4 to reproduce normal growth. However, in a simulation using this migration rate, the DTC pulled ahead of distal germ cells (Fig. 5A). We therefore ran a second simulation using the same migration rate, but forcing the DTC
to pause whenever it pulled ahead of distal germ cells. This alternative modeling choice maintained the proliferative zone, but produced a shortened adult gonad (Fig. 5B). By contrast, when proximal “stretching” was included in the model by moving the turn, simulations produced a reasonably sized gonad, while keeping the organ filled with germ cells as *in vivo* (Fig. 5C). We conclude that elongation of the proximal region during late L4 is a non-negligible component of normal gonadogenesis. We speculate that germ cells exert pressure on the turn, forcing the gonad to “stretch” during late L4.
Fig. 5. Gonadogenesis by DTC migration alone produces unrealistic simulations. (A) The outcome of a simulation in which gonad growth occurs by rapid DTC migration alone (no stretching). (B) The same simulation as (A) with DTC pausing (see text). (C) A simulation including proximal “stretching” in addition to DTC migration, consistent with measurements in vivo.
Adult proliferative zone homeostasis may require mechanical feedback

In the course of model building, maintaining a stable number of proliferative cells in the young adult proved problematic. Initially, we tried to achieve cell number homeostasis by balancing a fixed adult cell division rate with a fixed death rate. Fig. 6A and B demonstrate how this approach failed. These simulations always produced an unrealistic explosion in the number of proliferative cells, even when the death rate was increased to the extent that ovulation was impaired. No germ cell death rate in this range was sufficient to balance a cell cycle length of 8 hours. The same was true for a longer cell cycle length of 24 hours (the longest estimate in the literature (Crittenden et al., 2006)). We also tried introducing mechanical feedback on cell death by making heavily compressed germ cells more likely to undergo apoptosis. However, this caused ovulation to halt following excessive cell death. Of the mechanisms we have simulated thus far (changing rates of proliferation, of movement as influenced by cell-cell repulsion, and of cell death), negative feedback from compression on germ cell proliferation rates provided the most robust homeostasis.
Fig. 6. Strategies for stabilizing proliferative cell numbers. (A) and (B): Attempts to balance rates of cell proliferation and death in the absence of mechanical feedback. Both panels show the number of proliferative cells in the simulation over time for three different values of the death rate (mean of 5 runs). A horizontal red dashed line indicates the expected proliferative cell count. (C) Left: A comparison of proliferative zone mitotic index in wild type and in the ced-3(n717) mutant at 1 and 2 days post L4. Statistics: Mann-Whitney U test, where * is $p < 0.05$. Right: Internuclear Distance index as calculated from the same animals. Statistics: two-tailed Student’s t-test where **** is $p < 0.0001$. The number of gonad arms analyzed: 33 (N2 D1), 23 (ced-3(-) D1), 22 (N2 D2), 21 (ced-3(-) D2).
If mechanical feedback on the cell cycle were to occur \textit{in vivo}, one prediction is that tighter packing of cells in the proliferative zone should slow the cell cycle. We sought an experimental means to induce tighter packing without manipulating key signaling pathways that regulate the size, number, or fate of cells in the zone, and then asked whether the mitotic index of these more densely-packed cells was altered. We examined a \textit{ced-3} mutant in which oogenic germ cells fail to undergo physiological cell death. We reasoned that in this mutant, the larval germ line should develop normally, but that the accumulation of “un-dead” cells in the loop region might pose a barrier to germ cell movement and thereby cause compression of distal cells. Indeed, at day 2 we found a lower internuclear distance among cells in the proliferative zone in the \textit{ced-3} mutant as measured along the long (distal-proximal) axis (Fig. 6C; we found a similar internuclear distance difference along the short axis of the gonad, while the number of cells in the proliferative zone was not significantly different). We then measured mitotic index and found that while it is indistinguishable from wild type early in adulthood (Fig. 6C, day 1), it is significantly reduced relative to wild type after one day of oogenesis (Fig. 6C, day 2), correlating with greater compression and accumulation of “un-dead” cells. These results are consistent with the possibility that tightly-packed cells might cycle more slowly in response to local mechanical force.

\textbf{In silico cell tracking and clonal analysis}

Live cell tracking and live/fixed-sample cell lineage analyses are experimental gold standards in developmental and stem cell biology, but these techniques are not yet implemented for the \textit{C. elegans} germ line. Long-term live cell tracking is difficult due to germ line sensitivity to stress conditions, but recent advances in germline transgene expression (Zeiser et al., 2011) may facilitate lineage analysis. Nevertheless, analysis of labeling data in the \textit{C. elegans} germ line is complicated by fast gonad growth and the relatively short time the system remains in homeostasis (Killian and Hubbard, 2005; Qin and Hubbard, 2015). \textit{In silico} models represent a complementary tool for testing hypotheses about germ cell dynamics, providing predictions for the corresponding experiments. We therefore incorporated cell tracking and lineage recording capabilities into our model.
First, the paths taken by a small sample of germ cells and their descendants were traced (Fig. 7). Three cells were labeled in early L3, one from each of the distal, mid and proximal regions of the gonad arm. The simulation showed that descendants of a single cell remained tightly grouped initially. During L3 the dominant direction of cell movement was toward the DTC; this reversed in adulthood (see Fig. 7, 35.5 - 43.5 hours, and Movie S1). Going into L4, the distal-most cells (red) travelled further and faster than proximal cells, filling the space created by DTC migration. The distal-most cells also produced more descendants, since they remained longer in the proliferative zone during gonadogenesis. Meanwhile, proximal cells (blue) remained pressed into the proximal end and eventually developed into sperm. Later in L4, all clonal groups became more dispersed, particularly in the mid-gonad. Some germ cell movement toward the turn also occurred over this period, as cells moved to fill the space created by stretching (Fig. 7, 33.5hr post-hatching).
Fig. 7. Tracking individual germ cells. Three cells were labelled at the beginning of L3: one distal (red), one mid (green) and one proximal (blue). The three columns of the figure show the paths taken by each of these cells, along with their descendants. Other germ cells are indicated in light grey. Note that some tracks do not end in a cell, due to removal from the simulation by apoptosis or ovulation; this is particularly apparent at 109.5hph, as green oocytes are ovulated.
Tracking into adulthood showed that the descendants of the proximal-most cells at L3 were eliminated from the gonad by apoptosis, or ovulation and fertilization (note the few remaining green and blue cells at the final time point). However, multiple ancestor labels remained in the simulated germ line when self-sperm were depleted. This observation is of interest concerning the possibility of achieving monoclonality, in which all adult cells descend from a single labeled ancestor. Monoclonality indicates a neutral drift maintenance mechanism (Snippert et al., 2010). While not explicitly required, our model allowed neutral drift to occur. However, the lineage tracing we implemented suggests that to observe monoclonality experimentally in *C. elegans*, ovulation would need to be prolonged beyond the time of self-sperm depletion (e.g. by mating).

To provide an overview of the motion and arrangement of all germ cells, we ran a simulation labelling every cell according to its L3 ancestor (Fig. 8). It confirmed that the distal-proximal position of cells is roughly maintained throughout a development simulation. Cells near the DTC at L3 contributed to the adult proliferative zone, while proximally positioned cells at L3 became self-sperm. Clonal groupings of cells appear at the distal end in this simulation, while considerable mixing occurs in the mid-gonad. It remains to be seen whether these predictions will match experimental observations, once techniques become available for *in vivo* cell tracking.
Fig. 8. **Labelling all young adult germ cells by their L3 ancestors.** All germ cells present at the start of L3 were assigned a color that was inherited by daughter cells. The lower image shows the resulting pattern of cell ancestor labels in the adult simulated germ line.
Discussion

Our current model of the *C. elegans* germ line builds on previous work and suggests new avenues of investigation. Germ cells are simulated in 3D using a combination of off-lattice cell mechanics and a logic-based response to signaling. Modeling the germ line in 3D, as well as the gonad architecture and rachis, provides a more realistic simulation. The addition of mechanics provides physical interactions among cells and naturally recapitulates germ cell movement over time, most notably a general reversal in early adulthood. The model also enforces a leader cell boundary condition, parameterized using new experimental measurements. By this approach, we obtained reasonable agreement between simulation and a range of experimental data.

The introduction of two hypothesis-generating effects not yet described in the literature greatly enhanced the fit: “stretching” gonad growth during L4 and a contact inhibition-like mechanism among adult germ cells. In addition to the rapid germ cell proliferation that contributes to early anterior-posterior gonad growth (Killian and Hubbard, 2005), our model suggests that the whole organ is affected by germ cell pressure during late L4, leading to stretching and centrifugal movement of the turn. We could not produce a realistic model without incorporating this mechanism.

An exciting prediction made by the model is that adult germ cells may be subject to mechanical feedback similar to contact inhibition. Contact inhibition is a common assumption in cell-based computer models (Buske et al., 2011; Galle et al., 2005; Dunn et al., 2012), but other means to stabilize cell numbers in a germ line simulation exist. For instance, germ cells could be made highly incompressible. However, the repulsion force between cells in our simulation is already stronger than similar cellular models (Meineke et al., 2001), and changing the strength of cell repulsion would also alter the ovulation rate, an aspect of the current model that fits the data well. Another possibility is that as yet uncharacterized mechanisms controlling the rate of entry into or progression through meiotic prophase could counter the accumulation of proliferative germ cells.
Mechanical feedback on proliferation is an attractive hypothesis. In addition to being a robust mechanism for homeostasis during the maintenance phase, it could explain why germ cells cycle faster during larval expansion and slow after gonad growth stops. Remarkably, we found denser packing correlated with a reduced proliferation rate, as predicted. Though this correlation is consistent with a mechanical feedback mechanism, additional experimental tests of this hypothesis are needed. Contact inhibition is a major tumour suppressor mechanism (Hanahan and Weinberg, 2011), but its role as a regulator of normal tissue development and homeostasis is not well understood. If our prediction is borne out, the *C. elegans* germ line could provide a powerful *in vivo* model. Future work would also have to account for the apparent violation of this mechanism among mutants such as *glp-1(gf)* (Maciejowski et al., 2006). One attractive candidate mediator is the Hippo signalling pathway (Edgar, 2006). Components exist in the *C. elegans* genome (Yang and Hatta, 2013) but their role in germline development has not been explored.

Two other computational models of the *C. elegans* germ line appeared while this work was in revision (Hall et al., 2015; Chiang et al., 2015). Hall et al. (2015) also combines 3D, mechanically driven cell movement with a logical model of cell behavior. A major difference is that our model simulates both larval and adult stages, whereas Hall et al. simulate the adult germ line only (including genes that control oocyte maturation and cell death). Interestingly, both models found it necessary to limit mitotic growth by introducing negative feedback from pressure on germ cell proliferation. Also, neither model produced a monoclonal germ line in labelling simulations. A more detailed comparison of our work with that of Hall et al. (2015) will require access to their code and additional details regarding the qualitative network model. In contrast, Chiang et al. (2015) takes a lattice-based approach to germ cell movement, and focuses on identifying cell cycling strategies that minimize the accrual of mutations while still allowing for rapid expansion of the germ cell pool.

Since our work represents a first-generation 3D mechano-logical model of the germ line, there remain ways in which our simulations fall short of the real system. For instance, the turn in our simulations is somewhat crowded, containing a cluster of germ cells rather
than a queue of cells of increasing size. This might be remedied in future by incorporating local narrowing of the gonad turn boundary, or prescribing flow from the rachis or other signals to regulate oogenic cell growth (Wolke et al., 2007; Nadarajan et al., 2009; Govindan et al., 2009).

In general, long simulation run time has hindered our ability to explore the full parameter space of the model systematically. Thus, another choice of parameters may yet exist producing a better fit to data. We have, however, varied the unconstrained parameters about their current values (Figs. S4-S9) and varied two key parameters simultaneously (adult cell cycle length and cell-cell repulsion; Fig. S10). This analysis suggests that larval cell cycle time bears on multiple aspects of germline development, consistent with previous findings (Killian and Hubbard, 2004; Michaelson et al., 2010; Korta et al., 2012, Setty et al., 2012). Variations in this parameter impacted gonad growth, sperm count, proliferative zone accumulation and meiotic entry. These effects contrast with variation in other experimentally undetermined parameters that do not alter germline growth dynamics. While variation in the position at which sex determination occurs affects sperm count (and, modestly, the proliferative zone due to compression changes), we note that the distance-based implementation of this feature is somewhat artificial. Therefore, these impacts should be revisited when a more biologically-based mechanism for sex determination is implemented, such as coupling to meiotic entry (Barton and Kimble, 1990).

Finally, we have simplified the system in certain respects to make it more tractable. For example, although we took into account radial gonad growth, local alterations in radius at the distal tip and turn are neglected. This may bear on the fit between cell row counts and micron measurements of the proliferative zone. Despite these areas for improvement, the model provides a strong starting point on which to build in future work.

Future investigations using this model could also further develop the cell statechart. For example, it will be of interest to challenge the model under conditions that interfere with glp-1 activity and/or cell cycle progression. In addition, the impact on gonadogenesis and
cell dynamics of mutations affecting cell size could be studied \textit{in silico} (Arur et al., 2009; Korta et al., 2012). Finally, the modeling approach described here could be applied to other developmental systems, such as intestinal organoids (Sato et al., 2009).

To conclude, we have developed and tested a detailed \textit{in silico} model of the \textit{C. elegans} germ line, that combines, for the first time, a 3D mechanics simulation with a statechart model of cell behavior to generate new predictions. These include a role for germ cell pressure in multiple aspects of gonadogenesis and possible mechanical feedback on the adult germ cell cycle.
Materials and Methods

Cell mechanics and boundary condition

The mechanics simulation uses Chaste, an open source biological modeling library (Mirams et al., 2013). Germ cells were represented as deformable spheres, while a gonad boundary was imposed that follows DTC migration. Please see supplementary materials and methods for details on both of these features.

Intracellular model and progression during a simulation

While the mechanics simulation governs cell movement and death, intracellular aspects of the model are governed by a statechart (Fig. 2C and supplementary materials and methods). The statechart contains orthogonal regions controlling the cell cycle, response to DTC signaling, and sex determination. We describe below how each region acts during a simulation.

Germ cells present at the start of the simulation are in the initial states colored red on Fig. 2C. Thereafter, daughter cells inherit their parent’s state.

In the CellCycle region, cells are initially in Mitosis and cycle through the phases G1, S, G2 and M, dividing on entry into M phase. The transition out of a phase occurs after a certain time delay. To avoid synchronized cell cycles, the durations of G1 and G2 are sampled from a normal distribution, with mean $\mu$ and standard deviation $s\mu$ ($s=0.1$). $s$ is a stochasticity parameter, while $\mu$ is the expected phase length. Expected phase lengths are given in Table S1 and increase between mid-L4 and adulthood. A mechanical feedback mechanism is applied to adult germ cells only, which transiently arrests progress through the cell cycle whenever a cell’s volume falls below 70% of its rest value. The rest volume of a cell is simply the volume of a sphere of the same radius. The compressed volume is calculated by taking into account deformation due to neighboring cells (see supplementary materials and methods). For this model, we chose to delay the cell cycle in the G2, as this portion of the cell cycle is sensitive to other cues such as nutrition.
Germ cells in the model exit mitosis only when they enter G1 within a region where GLD-1 or GLD-2 is active. Therefore, cells that complete G1 (that is, are in S or G2) as they enter an active GLD region will divide once (and only once) prior to becoming NonProliferative. Upon exiting mitosis, a fixed length G1 and meiotic S occur before the cell enters meiotic prophase. We note that these cell cycle choices – G2 for sensitivity to compression and G1 for commitment to meiosis – can be altered in future versions of the model in response to new experimental results. Meiotic cells grow steadily, up to a maximum radius of 4µm.

Several statechart regions deal with the response to LAG-2/APX-1. The GLP-1 receptor is initially Unbound. At <35µm from the DTC, the GLP-1 receptor becomes Bound. LAG-1 then activates, GLD-1 and GLD-2 inactivate, and the cell remains in mitosis. At ≥70µm from the DTC, the GLP-1 signal becomes Absent. LAG-1 switches off, and the GLD pathways promote meiotic entry.

In the SexDetermination region of the statechart, all cells begin as Precursors, and make a sperm/oocyte fate decision on reaching 200µm from the DTC. If this decision occurs before 32.5hph the cell will be sperm-fated, otherwise it is oocyte-fated. After a short delay, sperm-fated cells divide twice to produce four sperm. Meanwhile, oocyte-fated cells grow steadily and are considered mature on reaching 10µm in radius. For growth rates see Table S1. Oocyte-fated cells only may be removed by apoptosis (Jaramillo-Lambert et al., 2007; Gumienny et al., 1999), which occurs with probability $p$ for each hour spent outside the adult proximal gonad (<250µm from the DTC). $p$ is given in Table S1. It is assumed that oocyte-fated cells which reach the proximal gonad are committed to becoming mature gametes. At the proximal end of the oviduct, oocytes are removed from the simulation along with one sperm.
Parameter set and software

Table S1 lists parameter values and their sources, and indicates which parameters were varied during fitting. A 100 hr simulation takes 10-12 hr on one core of an Intel Core i5 machine.

To reproduce our results, Chaste and its dependencies must be installed (https://chaste.cs.ox.ac.uk/trac/wiki/InstallGuides/InstallGuide). Additional files specific to this project can then be downloaded (https://github.com/Katwell/ElegansGermline). All code is covered by a 3-clause BSD license; see Chaste website. The model outputs vtu files for visualization in Paraview (Henderson et al., 2012), and text files from which graphs were generated in R. Further instructions and scripts are included in the Github download.

Experimental methods

Determining larval gonad dimensions: Worms were grown at 20°C with abundant food. Developmental stage was determined by vulval morphology. DIC images of live worms were captured, and measured using ImageJ (Schneider et al., 2012). Figure S3 shows each measurement, while Table 1 summarizes the results. In addition, 1µm Z-stacks were obtained from live worms containing a germ cell membrane GFP marker (xnSi1; Chihara and Nance, 2012) to estimate the radius of germ cells and of the rachis.

Mitotic index and internuclear distance: In parallel, wild-type and ced-3(n717) mutant worms were synchronized, ethanol fixed and DAPI stained as described in (Pepper et al., 2003). Microscopy and determination of mitotic index were as described in (Michaelson et al., 2010). Internuclear distance index is the distance from the distal tip to meiotic entry in µm over the distance in CD.
<table>
<thead>
<tr>
<th>Approximate hours post-hatching</th>
<th>Mid L3</th>
<th>L3/L4 molt</th>
<th>Mid L4</th>
<th>Young adult</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22</td>
<td>26</td>
<td>31</td>
<td>35.5</td>
</tr>
<tr>
<td>Sample size</td>
<td>10</td>
<td>10</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Length of proximal region (μm)</td>
<td>61.7 (9.33)</td>
<td>56.1 (6.16)</td>
<td>53.0 (12.3)</td>
<td>126 (21.5)</td>
</tr>
<tr>
<td>Length of distal region (μm)</td>
<td>NA</td>
<td>12.3 (4.02)</td>
<td>118 (17.8)</td>
<td>248 (25.6)</td>
</tr>
<tr>
<td>Length of turn (μm)</td>
<td>NA</td>
<td>23.1 (2.95)</td>
<td>27 (2.59)</td>
<td>30.8 (4.86)</td>
</tr>
<tr>
<td>Total length (μm)</td>
<td>61.7 (9.33)</td>
<td>91.4 (7.76)</td>
<td>198 (23.3)</td>
<td>405 (46.7)</td>
</tr>
<tr>
<td>Proximal radius (μm)</td>
<td>5.48 (1.36)</td>
<td>6.37 (1.02)</td>
<td>7.73 (1.62)</td>
<td>12.3 (3.17)</td>
</tr>
<tr>
<td>Distal radius (μm)</td>
<td>NA</td>
<td>5.80 (0.939)</td>
<td>8.21 (1.24)</td>
<td>10.3 (1.06)</td>
</tr>
<tr>
<td>Mean radius (μm)</td>
<td>5.48</td>
<td>6.09</td>
<td>7.97</td>
<td>11.3</td>
</tr>
</tbody>
</table>

Table 1. Mean *C. elegans* gonad dimensions throughout development. S.d. in brackets. Some variation stems from slight age differences between worms of the same developmental stage. Staging hours from (Wood et al. 1980).
Acknowledgments

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Author contributions

KA wrote the computer model and carried out simulations. ZQ carried out the experimental work. All authors contributed to model development, analysis and interpretation of data, and preparing the manuscript.
References


Supplementary Information

Figure S1. Experimentally determined rates of gonad growth. Shows the total linear growth rate (red), radial growth rate (green) and proximal arm growth rate (blue) for the *C. elegans* gonad over time, according to our measurements. Shaded regions are ±1 s.d.. Growth rates are based on the difference between two length measurements made at the start and end of each developmental phase. The rates shown were used as input parameters to the simulation with some additional processing (for instance, the DTC migration rate is based on the total linear growth, minus any length that can be accounted for by proximal arm elongation).
Figure S2. Simulated micron measurements of the proliferative zone. Panel (A) shows the distance from the DTC to the proximal-most cell in mitosis, while (B) shows the distance from the DTC to the distal-most cell in meiosis. (C) shows the length of the meiotic entry region, defined by Hansen et al. in 2004 as the region of overlap between proliferative cells and cells in prophase of meiosis I. The simulated lengths in (A) and (B) are longer than the corresponding experimental measurements, particularly just after the model transitions from larval to adult behavior. Together with the fact that simulated cell row counts do match experiment well, this suggests that the effective length of a cell row in the model is slightly too long; either because cells in the real germ line are smaller or because they are under greater compression. The second possibility is more likely, as it is the harder parameter to estimate. However, our main conclusions herein would in fact be strengthened if germ cells are under greater compression than our current model estimates.
Figure S3. Positions at which DIC microscopy images were measured. Corresponds to the measurements in Table 1. Dotted lines show the paths drawn onto each DIC image and measured using ImageJ.
Figure S4

Varying larval cell cycle duration in hours

Gonad length

Sperm count

Total cell count

Proliferative cell count

Position of last proliferative cell

Position of first meiotic cell

Development • Supplementary information

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Figure S5

Varying the delay in hours between onset of meiosis and mature sperm production

- Gonad length
- Sperm count
- Total cell count
- Proliferative cell count
- Position of last proliferative cell
- Position of first meiotic cell
Figure S6

Varying the distance in µm from the DTC at which sex determination occurs

- **Gonad length**
- **Sperm count**
- **Total cell count**
- **Proliferative cell count**
- **Position of last proliferative cell**
- **Position of first meiotic cell**
Figure S7

Varying meiotic cell growth rate in microns per hour

- Gonad length
- Sperm count
- Total cell count
- Proliferative cell count
- Position of last proliferative cell
- Position of first meiotic cell
Figure S8

Varying death rate

Gonad length

Sperm count

Total cell count

Proliferative cell count

Position of last proliferative cell

Position of first meiotic cell

Gonad length (µm)

Sperm count

Total cell count

Proliferative cell count

Position from DTC (µm)

Time (hph)
Figures S4-S9. Parameter sweeps showing the effect of a 25% variation in each of the model's free parameters. Free parameters are those that could not be adequately determined from experimental data; these are indicated by a * in Table S1. Supplementary Figures 4-9 show variations in, respectively: larval cell cycle length, delay between meiosis and sperm production, position at which sex determination occurs, meiotic cell growth rate, death rate and cell-cell repulsion strength. Each line is the mean of 5 runs, and the vertically shaded region is ±1 s.d.
Figure S10. A parameter sweep varying adult cell cycle length and cell-cell repulsion force, in the absence of contact inhibition-like mechanical feedback. A sweep aimed at determining whether a stable proliferative cell count can be maintained without mechanical feedback, by altering the parameter set. For cell cycle lengths in the range 8-24 hrs the proliferative cell count still increased beyond normal levels. Each line is the mean of 5 runs, while the vertically shaded region is ±1 s.d.. Cell counts have been sliding window averaged using a window length equal to half the cell cycle duration, in order to remove phasing and make the general trend more apparent. The final panel compares raw and averaged data for a single choice of parameters.
Table S1. Parameter values and sources. All times are given as hours post-hatching. † From our measurements of microscopy images of the gonad. * Indicates parameters that were tuned to fit the experimental data in Fig. 4. Other parameters were considered fixed based on available data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial conditions:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starting time</td>
<td>18.5 hr</td>
<td>(Wood et al., 1980)</td>
<td>Beginning of L3</td>
</tr>
<tr>
<td>Initial germ cell count</td>
<td>16</td>
<td>(Stupay and Hubbard, 2003)</td>
<td></td>
</tr>
<tr>
<td>Initial gonad length</td>
<td>32 μm</td>
<td>(Stupay and Hubbard, 2003)</td>
<td></td>
</tr>
<tr>
<td>Initial gonad radius</td>
<td>5.48 μm/ hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Stretching:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate of stretching growth during late L4</td>
<td>16.2 μm/ hr</td>
<td></td>
<td>Based on comparing proximal region length at mid L4 and in the adult</td>
</tr>
<tr>
<td>Period of stretching growth</td>
<td>31 - 35.5 hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>DTC migration:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L3 moult - mid L3</td>
<td>8.77 μm/ hr</td>
<td></td>
<td>Based on change in total gonad length</td>
</tr>
<tr>
<td>Mid L3 - L3/L4 moult</td>
<td>7.43 μm/ hr</td>
<td></td>
<td>Based on change in total gonad length</td>
</tr>
<tr>
<td>L3/L4 moult - mid L4</td>
<td>21.3 μm/ hr</td>
<td></td>
<td>Based on change in total gonad length</td>
</tr>
<tr>
<td>Mid L4 - young adult</td>
<td>13.6 μm/ hr</td>
<td></td>
<td>Change in length – proximal growth</td>
</tr>
<tr>
<td>DTC halts</td>
<td>35.5 hr</td>
<td>(Stupay and Hubbard, 2003)</td>
<td></td>
</tr>
<tr>
<td><strong>Radial growth:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L3 moult - mid L3</td>
<td>0 μm/ hr</td>
<td></td>
<td>Our estimate</td>
</tr>
<tr>
<td>Mid L3 - L3/L4 moult</td>
<td>0.153 μm/ hr</td>
<td></td>
<td>Based on average radius measurement</td>
</tr>
<tr>
<td>L3/L4 moult - mid L4</td>
<td>0.376 μm/ hr</td>
<td></td>
<td>Based on average radius measurement</td>
</tr>
<tr>
<td>Mid L4 - young adult</td>
<td>0.74 μm/ hr</td>
<td></td>
<td>Based on average radius measurement</td>
</tr>
<tr>
<td><strong>Turning:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radius of the turn</td>
<td>11.5 μm</td>
<td></td>
<td>Adult proximal &amp; distal arms almost touch</td>
</tr>
<tr>
<td><strong>Time at start of turning</strong></td>
<td>23 hr</td>
<td><em>(Stupay and Hubbard, 2003)</em></td>
<td></td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------</td>
<td>-------------------------------</td>
<td></td>
</tr>
</tbody>
</table>

| **Cell sizes:** |
|-----------------|-------|-------------------------------|
| Mitotic germ cell radius | 2.8 μm | † |
| Meiotic germ cell radius | 4 μm | *(Maddox et al., 2005; Nadarajan et al., 2009)* |
| Oocyte radius | 10 μm | Oocytes fill the proximal arm |
| Sperm radius | 1.5 μm | *(Shakes et al., 2011)* |
| Cell growth rate | 1.0 μm/hr | * |

| **Force law:** |
|------------------|-------|-------------------------------|
| Baseline drag coefficient η | 1 | *(Dunn et al., 2013)* |
| Strength of repulsion μ | 50 | * |

| **Cell cycle:** |
|-----------------|-------|-------------------------------|
| Larval cell cycle duration | 3 hr | *(Kipreos et al., 1996)* |
| Adult cell cycle duration | 8 hr | *(Fox et al., 2011)* |
| Estimated phase breakdown | 2% G1 57% S 39% G2 2% M | *(Fox et al., 2011)* |
| Period over which germ cell cycle length increases | 31 – 35.5 hr | *(Korta et al., 2012)* |
| **Other parameters:** |
| Distance at which GLP1 signal becomes absent | 70 μm | *(Stupay and Hubbard, 2003)* |
| Position at which sex determination occurs | 200 μm | * |
| Sperm/oocyte switch time | 32.5 hr | *(Barton and Kimble, 1990)* |
| Sperm production delay | 2 hr | * |
| Distance from the DTC at which oocyte growth | 250 μm | Just beyond the start of the proximal arm. Allowing |
begins

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<thead>
<tr>
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<th>Supplementary information</th>
</tr>
</thead>
</table>

| Stochasticity $s$ | 0.1 | Arbitrary, prevents synchronised divisions |
| Hourly apoptosis probability $p$ | 0.025 | Produces sustained ovulation with a reasonable rate |

Table S2. Cell counts for a single run. These counts apply to the run depicted in Figure 3 of the main text only.

<table>
<thead>
<tr>
<th>Time (hours post-hatching)*</th>
<th>18.5</th>
<th>27.5</th>
<th>30.5</th>
<th>32.5</th>
<th>33.5</th>
<th>35.5</th>
<th>60.5</th>
<th>87.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proliferative + Meiotic S (yellow cells)</td>
<td>16</td>
<td>113</td>
<td>147</td>
<td>184</td>
<td>174</td>
<td>228</td>
<td>366</td>
<td>314</td>
</tr>
<tr>
<td>Proliferative - Meiotic S</td>
<td>16</td>
<td>105</td>
<td>112</td>
<td>134</td>
<td>147</td>
<td>177</td>
<td>319</td>
<td>299</td>
</tr>
<tr>
<td>Meiotic S</td>
<td>0</td>
<td>8</td>
<td>35</td>
<td>50</td>
<td>27</td>
<td>51</td>
<td>47</td>
<td>15</td>
</tr>
<tr>
<td>Meiotic (green cells)</td>
<td>0</td>
<td>8</td>
<td>85</td>
<td>80</td>
<td>76</td>
<td>57</td>
<td>143</td>
<td>178</td>
</tr>
<tr>
<td>Sperm/ Spermatogenic (blue cells)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>38</td>
<td>38</td>
<td>152</td>
<td>111</td>
<td>47</td>
</tr>
<tr>
<td>Oogenetic (pink cells)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>36</td>
<td>69</td>
<td>60</td>
<td>83</td>
</tr>
<tr>
<td>Meiotic + Spermatogenic + Oogenetic</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>118</td>
<td>150</td>
<td>278</td>
<td>314</td>
<td>308</td>
</tr>
</tbody>
</table>

*In later time points gametes are lost to fertilization.
Movie 1. A germline simulation recorded throughout larval development and into adulthood.
Parameters as listed in Table S1.
Supplementary Materials and Methods

This section is intended to further clarify certain details of the computational model, namely: (1) the mathematics of the cell mechanics model, (2) how the boundary condition is implemented, (3) how a statechart updates over time, and (4) how mechanical feedback on the cell cycle is applied.

1) Cell Mechanics

The mechanics simulation uses Chaste, an open source C++ biological modeling library (see Mirams et al., 2013). Each germ cell is represented by a deformable sphere. When cells $i$ and $j$ overlap, cell $i$ experiences a repulsion force given by:

$$F_{ij} = \mu (R_i + R_j) \log \left( 1 - \frac{d_{ij}}{(R_i+R_j)} \right) r_{ij},$$

where $r_{ij}$ is the unit vector from $i$ to $j$, $R_i$ and $R_j$ are cell radii, $d_{ij}$ is the length of the overlap between the cells, and $\mu$ is a spring strength constant. Given the force law in (1), cell positions are updated using forward Euler time stepping and assuming the overdamped form of Newton’s second law:

$$\eta \frac{dr}{dt} = F,$$

where $\eta$ is a drag coefficient and $F$ the net force on the cell found by summing all contributions. As a wide range of cell sizes are present in the germ line, we allow cell size to affect movement by increasing the drag coefficient linearly with cell radius. The final update equation for cell positions is:

$$r_i^{new} = r_i^{old} + dt \left( \frac{\eta R_i}{5} \right)^{-1} \sum_j F_{ij},$$

where $\eta$ is a drag coefficient appropriate for cells of radius 5 $\mu$m (Dunn et al., 2013).

2) Boundary Condition

Germ cells are confined to the gonad by a boundary that updates over time. To capture gonad growth, we explicitly model DTC migration and form a tubular boundary along its path. The DTC migrates in three prescribed stages; first travelling in a straight line along the ventral surface of the worm, turning onto the dorsal surface during the L3/L4 molt, then migrating back into the center of the animal and halting during the adult molt. The DTC’s target speed is fixed for each simulation stage, based on our experimental measurements of gonad dimensions. We additionally prescribe that germ cells must be no more than 5 $\mu$m (~1 cell diameter) behind the DTC for it to progress. This constraint prevents a biologically unrealistic gap opening up between the DTC and following cells.

As the DTC moves, a collection of equally spaced points on its path is stored, which
defines the organ midline (see panel A below). A small point separation of 2 µm ensures an accurate representation of the curved geometry. At each time step, if a cell is further from the midline than \((\text{gonad radius} - \text{cell radius})\), it lies outside the boundary and is moved toward the midline until it lies just inside again. Cells near the ends of the gonad are subject to a different position correction that generates hemispherical endcaps (see panel A).

Certain details specific to the \textit{C. elegans} gonad are also taken into account in the boundary condition. First, all germ cells in the distal region and turn are forced to lie just inside the boundary, forming a monolayer. An empty space representing the rachis is thereby created in the center of the organ. Second, our experimental measurements showed that the proximal gonad lengthens during L4, an effect that cannot be captured by moving the DTC. To reflect this, points on the midline of the turn are steadily shifted centrifugally during late L4, with new points added to maintain equal spacing (see panel B below).

![Boundary condition enforcement algorithm](image)

**Boundary condition enforcement algorithm.** (A) Indicates how germ cells are confined to the gonad, by correcting their positions relative to the DTC path. Cells in the endcaps are repositioned by being moved toward the end of the midline as required, generating a hemispherical cap. A dotted line in (A) indicates the shape of the resulting boundary condition. (B) Shows how the “stretching” of the gonad during late L4 is captured, by moving midline points in the turn, and inserting new points to maintain equal spacing.

3) Statechart Updates

The state of one of the 16 starting cells in our model is described by the chart below.
Only the initially active cell cycle phase may differ between starting cells; some may begin in G1, G2 or M rather than S phase.

Initial cell state. Red = active.

A transition out of this active set of states occurs whenever one of the transition conditions in square brackets is met. So for instance, since all cells are initially within 35 µm of the DTC, the condition is met for GLP-1 to become bound immediately. GLP-1 binds, and as a result LAG-1 activates and GLD-1/2 inactivate:

Cell state after one set of updates. GLP-1 binds, LAG-1 activates and GLD-1/2 inactivate.
When a cell moves further than 70 µm from the DTC, it meets the condition for GLP-1 to become Absent. As a result, LAG-1 becomes inactive and GLD-1/2 become active. There is no immediate effect on proliferative capacity unless the cell is also in the G1 state, as the transition arrow into NonProliferative comes from G1 only:

Subsequent changes in cell state follow similarly, occurring whenever a transition condition is met. Not all conditions are distance based; the sperm/oocyte fate decision depends on time post-hatching, the decision to exit proliferation depends on the cell cycle phase state of Mitosis as well as the states of GLD-1 and GLD-2, and the decision to advance to the next cell cycle phase depends on whether sufficient time has elapsed according to an internal counter. In addition, there are certain “actions” that are carried out while in a particular state (shown in blue). For instance, cells currently in Prophase of Meiosis I are instructed to grow, provided their current radius is < 4 µm.

Finally, cell movement and death are not part of the statechart model; they are handled separately in the mechanics simulation. Cell death is described in the main materials and methods.

4) Mechanical Feedback

As indicated in the statechart, proliferative cells count the amount of time they have spent in their current cell cycle phase, and move on to the next phase after a certain time delay has elapsed. This delay is determined on entry into the phase: for S and M phases the delay is fixed, for G1 and G2 it incorporates some randomness to avoid synchronisation (as described in the main materials and methods). In our model, this
counter temporarily pauses in G2 phase cells that are under “heavy compression”, leading to a transient G2 arrest.

A cell is defined to be under “heavy compression” if its current compressed volume is less than 70% of its rest volume. The rest volume of a cell is simply the volume of a sphere with radius $r$ equal to the cell radius:

$$V_{\text{Rest}} = \frac{4}{3} \pi r^3.$$ 

The compressed volume of a cell, meanwhile, is calculated by working out an Effective Radius ($R_{\text{Effective}}$) which takes into account the effect of neighbouring cells that overlap with the cell of interest (as in Dunn et al., 2013). Briefly, let:

$$R_{\text{Sum}} = \sum_{\text{Neighbors}} r - 0.5(r + r_{\text{Neighbor}} - d).$$

Where $d$ is the cell separation. If the number of overlapping cells is less than 12 (the number of neighbours expected in a maximally efficient sphere packing), then a correction term is applied to take into account the fact that the cell has extra space available in certain directions:

$$R_{\text{Effective}} = \frac{R_{\text{Sum}} + N^{*} r}{12},$$

where

$$N^{*} = 12 - N_{\text{Neighbors}}.$$ 

Otherwise no such correction is needed:

$$R_{\text{Effective}} = \frac{R_{\text{Sum}}}{N_{\text{Neighbors}}}.$$ 

The final compressed cell volume is the volume of a sphere with radius equal to the Effective Radius:

$$V^{*} = \frac{4}{3} \pi R_{\text{Effective}}^3.$$ 

References
