Deep learning for rapid analysis of cell divisions *in vivo* during epithelial morphogenesis and repair

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Highlights

- Accurate and efficient detection of epithelial cell divisions can be automated by deep learning of dynamic time-lapse imaging data
- Optimal division detection is achieved using multiple timepoints and dual channels for visualisation of nuclei and cell boundaries
- Epithelial cell divisions are orientated according to lines of tissue tension
- Spatio-temporal cell division analyses following wounding reveal spatial synchronicity that scales with wound size
- Additional deep learning tools enable rapid analysis of cell division orientation

Abstract

Cell division is fundamental to all healthy tissue growth, as well as being rate-limiting in the tissue repair response to wounding and during cancer progression. However, the role that cell divisions play in tissue growth is a collective one, requiring the integration of many individual cell division events. It is particularly difficult to accurately detect and quantify multiple features of large numbers of cell divisions (including their spatio-temporal synchronicity and orientation), over extended periods of time. It would thus be advantageous to perform such analyses in an automated fashion, which can naturally be much enabled using Deep Learning. Hence, here we have developed a pipeline of Deep Learning Models that accurately identify dividing cells in time-lapse movies of epithelial tissues *in vivo*. Our pipeline also determines their axis of division orientation, as well as their shape changes before and after division. This strategy has enabled us to analyse the dynamic profile of cell divisions within the *Drosophila* pupal wing epithelium, both as it undergoes developmental morphogenesis, and as it repairs following laser wounding. We show that the axis of division is biased according to lines of tissue tension and that wounding triggers a synchronised (but not oriented) wave of cell divisions back from the leading edge.

Introduction

Significant advancements in confocal microscopy mean that it is now possible to collect vast amounts of time-lapse imaging data from living tissues as they develop *in vivo* and as they respond to genetic or environmental perturbations (such as wounding). In parallel with the development of these imaging technologies, new methodologies are required in order to efficiently analyse these movies and extract detailed information about how the various cell behaviours (e.g. cell movements, divisions etc) contribute to tissue development and expansion, and how they enable repair responses following tissue damage (Etournay et al., 2015; Nestor-Bergmann et al., 2019; Olenik et al., 2023; Park et al., 2017; Scarpa et al., 2018; Tetley et al., 2019; Turley et al., 2022).

Computer vision (a form of artificial intelligence, AI) has progressed extensively in recent years, particularly with the development of Deep Learning Models (Guo et al., 2016; Voulodimos et al., 2018). Such algorithms can be trained to identify and classify objects in images, for example, enabling automated identification of tumours in MRI scans or segmentation of cells according to their type (Işin et al., 2016; Tran et al., 2018). These algorithms are particularly useful when analysing medical and biological data (Jones et al., 2017), because these data are often inherently 'noisy' as objects within a class can exhibit significant variation.

Deep learning algorithms excel at finding patterns in complex data (Guo et al., 2016). These abstract patterns in the deeper layers are often so complicated that they are difficult for the human eye to discern (Bhatt et al., 2020). In order to operate, deep learning algorithms must "learn" from "labelled data" i.e., data in which an expert has already performed the task that we require the model to automate (e.g., segmentation, classification etc). Using this 'training' data – which includes both the input and correctly annotated output (ground-truth) - the algorithm then learns how to complete the same task (Howard & Gugger, 2020). The resulting algorithms can be highly accurate at performing relatively simple vision tasks and are often much quicker than when the equivalent task is performed manually (Jones et al., 2017). This automated process allows efficient analyses of large datasets without extensive time-consuming repetitive work by a clinician or researcher. Furthermore, the high consistency of the resulting models reduces operator bias (or error), and guarantees the same level of accuracy across all experiments and studies.

In microscopy, deep learning has, so far, largely been applied to static images and has enabled relatively simple analyses, such as cell counting and quantification of object area (or volume), as well as more sophisticated tasks, such as the capacity to distinguish different cell types (Jones et al., 2017), and for detection of mitotic indexes in biopsy tissue sections which have notoriously poor manual reproducibility (Aubreville et al., 2020; Piansaddhayanaon et al., 2023). Whilst AI approaches are increasingly employed in (and beginning to revolutionise) digital pathology (Burlutskiy et al., 2020; Wang et al., 2022), Deep learning has been applied far less to the analysis of time-lapse video data, largely because these datasets are very difficult and time consuming to label (and without labelled data, we cannot train a model). Moreover, significantly bigger (and more complex) models will be needed to process videos compared to static images.

The biological tissue we investigate - the *Drosophila* pupal epithelium - is densely packed with nuclei and the developmental cell divisions are dispersed and rapid, each one occurring over a period of only several minutes. Moreover, as with most fluorescently-labelled live tissue, the pupal epithelium is somewhat prone to photo-bleaching, thus limiting the frequency at which sequential images can be collected whilst maintaining tissue health. All these factors need careful consideration as we attempt to develop a fully automatised algorithm, to detect and analyse the divisions with a high degree of accuracy. We have found that standard methods for tracking nuclei (such as TrackMate (Tinevez et al., 2017)) failed to cope with the constraints of our *in vivo* 3D imaging data and routinely confused epithelial cell divisions with migrating immune cells (that often contain nuclear material from engulfed apoptotic corpses), whilst also missing many clear (to the eye) mitotic events. However, while cell divisions in time-lapse movie data are often too dynamic for current methods for cell tracking, they do produce unique and reproducible patterns of motion. Hence, we turned to deep learning algorithms that have the power and flexibility to learn and subsequently detect these patterns.

In this study, we demonstrate how we train Deep Learning Models to extract information about the highly dynamic process of cell division within an epithelial field. For this, we have modified existing Deep Learning models previously used for static image analysis, adapting them to work on time-lapse videos with only a small increase in their computational cost. We combine this approach with a simple, but highly effective method for labelling our training data, which can then be used to entrain the models. Having established such a model, we go on to analyse cell divisions in time and space during epithelial morphogenesis and following wounding within living tissue in vivo. As expected, in the unwounded developing pupal epithelium we observe that cell divisions decrease linearly with time. However, wounding triggers a synchronous burst of cell divisions at 100 mins post-wounding, in a ring of epithelial tissue beginning several cell diameters back from the wound edge; this ring of proliferation becomes broader with increased wound size. In parallel, we have generated a related Deep Learning algorithm to determine the orientation of these cell divisions. We anticipate this Deep Learning algorithm could be widely applicable to the analysis of dynamic cell behaviours in a range of tissues that are amenable to study over extended time-courses, and, for such purposes, we have developed a publicly available plugin for use by others.

Results

A novel Deep Learning strategy efficiently identifies dividing epithelial cells in time-lapse imaging data

We chose to develop, and test the capability of, our model using the epithelium of the *Drosophila* pupal wing because of the optical translucency and genetic tractability of *Drosophila* which makes it easy to generate tissues with fluorescently labelled nuclei and cell boundaries (George & Martin, 2022; Weavers & Wood, 2016). The *Drosophila* pupal wing epithelium undergoes extensive growth through rapid cell divisions early in pupal life (Athilingam et al., 2021a; Paci & Mao, 2021), and can be imaged with high spatio-temporal resolution using live confocal microscopy. *Drosophila* pupae at 18 hours after puparium formation (APF) are first removed from their brittle, opaque puparium to reveal the transparent pupal wing (Weavers et al., 2018) (Fig. 1A). Since the wing epithelium is a relatively flat 2D cell sheet, composed of two opposing cell layers each one cell thick, imaging is largely in one plane. To analyse the cell behaviours involved in tissue repair, we use an ablation laser to generate sterile and reproducible wounds which heal rapidly within a few hours (Weavers et al., 2016). We further enhance reproducibility by localising our imaging and wounding to a particular region of the wing (Fig. 1B-D).

In order to gather training data to build an algorithm that can reliably detect cell divisions, we performed time-lapse imaging of unwounded and wounded pupal wings, with each movie lasting 3 hours (Fig. 1E-F). We generated a 3D z-stack (with z-steps of 0.75 μm in depth) that encompassed the entire epithelial cell layer at each time-point, which we then converted to a 2D image using a stack focuser tool (Umorin, 2002). For the wounded imaging data, the wounds we generated possessed a mean radius of 20μm (ranging from 9 to 30μm) with the smallest wounds closing 20 min after wounding and the largest wounds taking up to 90 min to fully close. Crucially, tissue wounding created a number of imaging complications that our algorithm needed to accommodate for. Firstly, wounding led to the epithelium around the wound edge moving out of the original focal plane and this reduced the image quality at the immediate wound edge. This was further exacerbated by a wound-associated reduction in the levels of the Ecadherin-GFP junctional reporter (Fig. 1E-F), which might be a consequence of the previously reported loosening of junctions in the migratory wound epithelium (Nunan et al., 2015; Razzell et al., 2014; Tetley et al., 2019). Secondly, wounding, by definition, leads to accumulation of local tissue debris, including bright nuclear material. Motile immune and fat cells, also with Histone2-RFP labelled nuclei, are recruited to the wound and both of these cell linages engulf tissue debris (Franz et al., 2018; Razzell et al., 2011); these non-epithelial cell types can be mistaken for dividing epithelial cells providing many opportunities for “false positives”. Finally, since pupae are living, developing organisms, they occasionally (and unavoidably) move during imaging, leading to sample drift in-between frames, and this also leads to the generation of false positives.

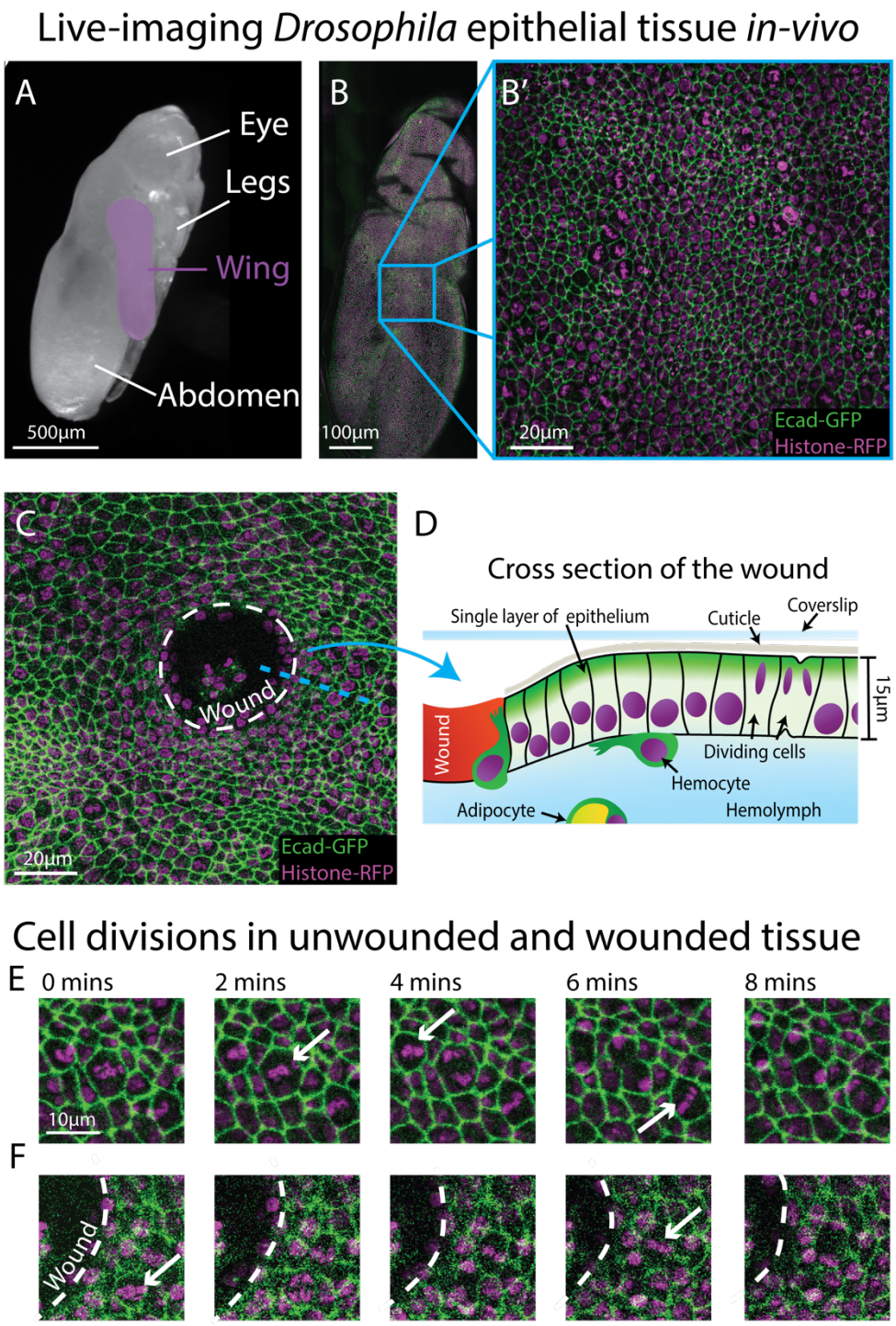

Figure 1. Live-imaging of Drosophila epithelial tissue dynamics in vivo. *A) Translucent Drosophila pupa with the pupal wing highlighted in magenta. B) The pupal wing (with magnified inset, B', on the centre zone of the wing where we consistently image) with cell boundaries labelled using E-cadherin-GFP (green) and nuclei with Histone2-RFP (magenta). C) Magnified view of the pupal wing epithelium after wounding, with the white dashed line indicating the wound edge. D) Schematic showing a cross section through the upper layer of epithelium of the pupal wing, with hemolymph (insect blood containing hemocytes and adipocytes) beneath and rigid cuticle above E) Multiple cell divisions (arrows) occur in the unwounded pupal wing epithelial tissue over the course of 8 minutes. F) A cell division (arrow) occurs in a wounded epithelial tissue with the white dashed line indicating the wound edge.*

In order to limit photo-bleaching of our biological samples, we chose to capture images every 2 minutes (Fig. 1E-F), which affords the sample over 1 minute of photo-recovery in between scans. Since the chromosomal separation phase of cell division (termed anaphase) takes approximately 6 mins in this specific tissue, the chosen frequency of imaging captures some details of each division, but is insufficient for application of a standard (non-deep learning) algorithm. Particle tracking algorithms, that link nuclei together by the distanced travelled, are also inappropriate to use here, since the pupal epithelial cells (and thus nuclei) are packed close together and dividing daughter nuclei would frequently (and mistakenly) be linked to a neighbouring nucleus rather than being associated with the parental cell.

We have overcome these various image analysis constraints by generating a new Deep Learning Model to locate cell divisions in space and time from complex 3D imaging data (Fig. 2). We use a ResNet34 model modified into a U-Net structure (He et al., 2016a; Ronneberger et al., 2015). ResNet is a widely used architecture for RBG image classification. However, here we not only want to know *whether* a division has occurred in a given period of time, but also to determine its *location* in space – and to do this we therefore use a U-Net structure. U-Nets were developed to segment images by classifying regions into categories. In our system, we classify epithelial cells into 'dividing' or 'non-dividing' (the latter represent the vast majority of cells) and by their location in space. To boost the model's capacity to segment time-lapse videos, we used the fast.ai libraries Dynamic U-Net class which can create a U-Net structure from an image classifier (see Materials and Methods for further details of the full model architecture). We envisioned a U-Net model based on a ResNet will be able to classify far more accurately than the standard U-Net model.

Development of Deep Learning Model 1 (U-NetCellDivision3)

Both the standard ResNet and U-Net models use 3 channel RGB images as an input. Here, our confocal z-stack images are composed of only 2 channels (E-cadherin-GFP, green, and Histone2-RFP, red; Fig.1E-F), leaving a spare channel for other potential inputs. The clearest features of a dividing cell occur as the duplicated chromosomes separate and move in opposite directions (seen in the Histone2-RFP channel, arrows Fig. 2A). Hence, we started developing our model by focusing only on the Histone2-RFP channel, and use 3 sequential time-lapse images of the Histone2-RFP (nuclear) channel (Fig. 2A), the 1st frame being when the cell is still in metaphase (before chromosomal separation, t=0 min) and the second and third in anaphase (during and after chromosome separation, t=2 and t=4 min respectively). Representing these three sequential frames in different colours and combining them into a single RGB image reveals a clear pattern with broadly symmetric stripes of red (centrally) followed by green and blue (extending outwards) (Fig. 2A). Crucially, there is a dramatic contrast between this triple coloured division pattern and that of non-dividing cells that are relatively stationary and so appear as a white/grey circular shape (Fig. 2A).

Our Deep Learning Model is trained to distinguish between these different RGB patterns and thus to accurately detect and locate cell divisions. To train the model, we first manually identified dividing cells in 20 independent time-lapse videos of unwounded and wounded tissue (this

generates 'labelled' training data); each training video consisted of 93-time frames (reflecting 186 mins of footage). In this training data, we detected 4206 divisions in total across all movies. Next, we generated an 'output' that we required the model to be able to reproduce. For this, we generated a "mask" video where every division was marked with a white circle (the same size as a cell about to divide) in the same location and at the correct time. The algorithm was then trained to reproduce this 'mask' (Fig. 2A).

We trained this deep learning algorithm which we term "U-NetCellDivision3". Next, we tested the model on new data that it had not previously seen and the results are shown in Table 1. The results ('outputs') are categorised into i) True positives (T_p) where a cell division has correctly been identified ii) False positives (F_p) where the model has incorrectly detected a cell division where one has not occurred and iii) False Negatives (F_n) where a cell division occurred but the model failed to detect it. We can then compute 'Dice score' (F1 Score) as a measure of the accuracy of the model, by combining T_p, F_p and F_n(Carass et al., 2020). The dice score is defined as:

$$\text{Dice score} = \frac{2T_p}{2T_p + F_p + F_n}$$

A dice score of 1 is a perfect score, whereas scores progressively smaller than 1 indicate a poorer algorithm performance. Dice scores for our algorithm "U-NetCellDivision3" indicate that this model detects only 78.7% of all cell divisions, and it led to many false positives (Table 1).

Development of Deep Learning Model 2 (U-NetCellDivision10)

To overcome the false positives and negatives associated with our initial model, U-NetCellDivision3, we extended the Deep Learning Model beyond a 3-frame input to increase the number of input frames to 10 (Fig.2B). Here, we included an additional time-point either side of the original 3-frame images, taking our input data to 5 timepoints in total, and extended the analysis to include both the E-cadherin-GFP and Histone2-RFP channels, thus incorporating both the dynamics of the cell nuclei and cell boundaries. Consequently, two of these timepoints show the cell in metaphase and three timepoints show the cell moving through anaphase into telophase and cytokinesis (Fig.2B). Although there should be little nuclear movement in these first two frames, including these additional metaphase images will help filter out false positives due to dynamic non-mitotic nuclei. In this new algorithm, in order to be identified as a dividing cell, the cell nuclei will need to be stationary in metaphase for two frames (2 minutes) before separating in a classical anaphase-like manor. Moreover, we also included the E-cadherin-GFP channel to provide additional information on cell boundaries and further enable the model to identify dividing cells. Indeed, it is well documented that cell boundaries change prior to division as cells increase their size and become rounder (Lancaster & Baum, 2014), and indeed this can be observed in the pupal wing tissue (Fig. 1B and C and Fig. 2B). Inclusion of the E-cadherin-GFP channel should also help rule out false positives (such as nuclear debris within the wound centre), which will lack a clear GFP-positive boundary. Inclusion of the E-cadherin channel is particularly helpful in concert with the additional 5th timepoint, as the cells can clearly be observed to separate as they move through telophase and cytokinesis.

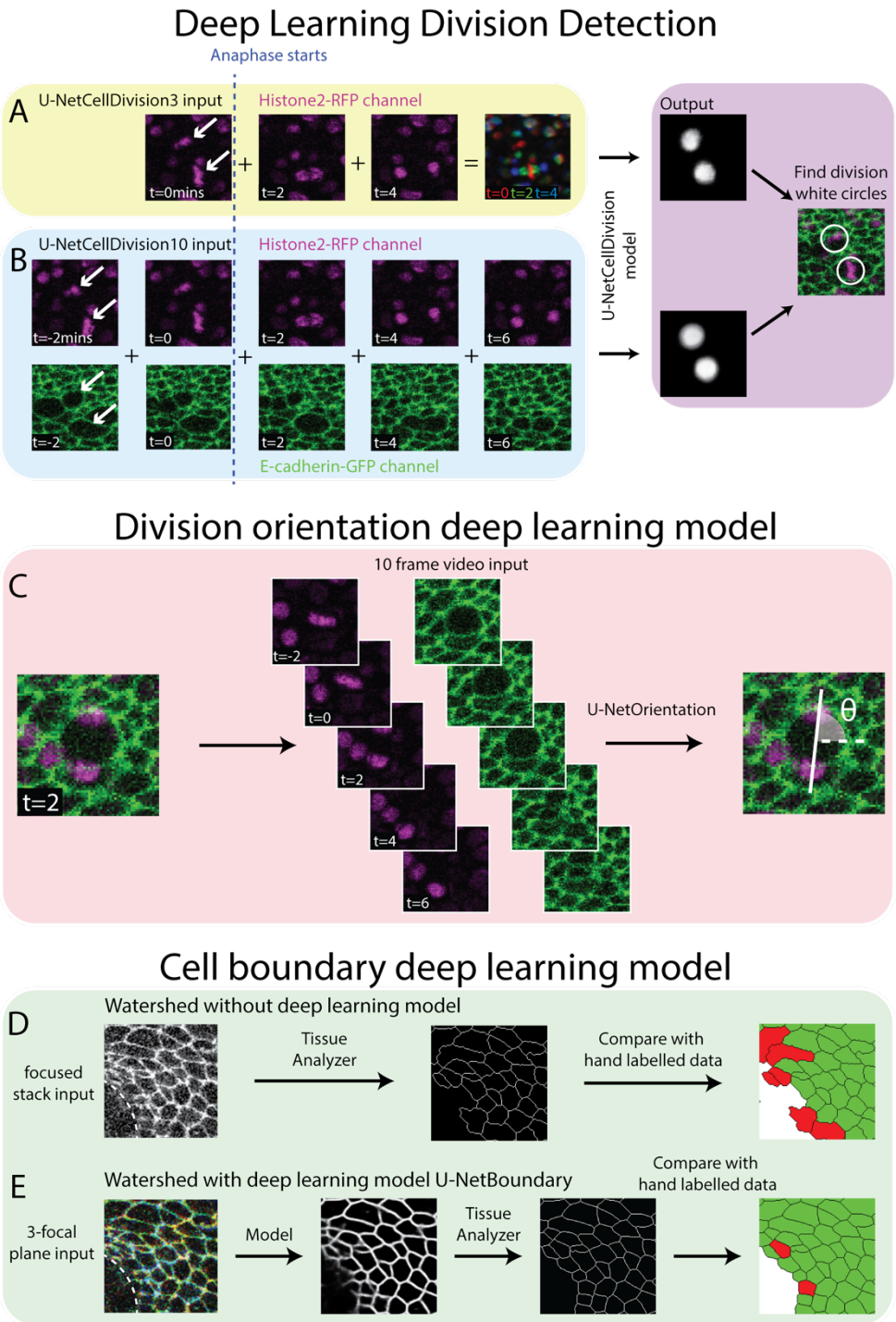

Figure 2. Deep Learning Detection of Cell Divisions, Division Orientation and Cell Boundaries. *Four novel deep learning models were developed to analyse epithelial cell behaviours. A) The first version of the division detection model receives 3 frames from the Histone2-RFP channel, which can be combined into a single RGB image, as is standard for a U-Net model. B) The second version of the model input has 10 frames, 5 each from the Histone2-RFP and E-cadherin-GFP channel. The model produces a white circle (white spot) where it detects a division. C) The cell division locations are then passed through the U-NetOrientation model to determine the division orientation. This model takes 10 frames of a division as the input. D) Segmentation of the focused cell boundaries without using a deep learning model. The focused stack image is inputted to Tissue Analyzer for segmentation and the result is compared to hand-labelled ground truth. Green cells are correctly segmented and red cells are incorrectly segmented. E) The 3-focal plane image is inputted into the U-NetBoundary model and then segmented using Tissue Analyzer; the result is then compared to hand-labelled ground truth.*

We subsequently trained the new model (Model 2) using the same three sets of videos (training, validation, and testing) as previously used to train Model 1. As shown in Table 1, there is now a significant (over 80%) reduction in both false positive and false negatives using the new 10-frame model. Most of the errors described previously have largely been resolved; a dice score above 0.95 means we can be far more confident in the results produced by U-NetCellDivision10. Supplemental Movie S1 shows the cell divisions that the algorithm has correctly identified; the orientations of the divisions are also revealed (see later). Now we have established a deep learning algorithm that can accurately (and quickly) identify and quantify cell divisions from our *in vivo* imaging data, we used the model to explore how (and where) cell divisions occur within a living, developing epithelial tissue in normal homeostatic conditions, and how this changes following an experimental perturbation such as wounding (Fig. 3 and Fig. 4). We also later extend this strategy to develop additional models to study different aspects of cell behaviour (shapes of cell boundaries and identification of cell division orientation planes, Fig.2C-E).

Cell divisions within unwounded epithelial tissue *in vivo* exhibit a 'community effect'

We first explored whether the new 'U-NetCellDivision10' algorithm can be used to quantify the numbers and locations of cell divisions within the unwounded pupal wing epithelium of *Drosophila*. We initially used our algorithm to compute 'division density' over space and time i.e., the number of divisions occurring in a given area at a given time (Fig. 3A). Interestingly, in the unwounded pupal epithelium, we observed that cells are more likely to divide close to and soon after previous divisions (Fig. 3B). To explore this phenomenon and determine whether cell divisions occur randomly across the unwounded tissue or whether they are more likely to occur close to other divisions, we calculated a space-time correlation for the cell divisions (see Methods for details). The space-time correlation is shown as a heatmap (Fig. 3B), with more intense red reflecting higher correlation. There is a high correlation close to the origin (within a 30μm radius and temporally, within 40 mins), which implies that cells are more likely to divide close to others in both space and time; this effect reduces with both increasing distance and time between cells. Consistent with previous studies of pupal wing morphogenesis (Etournay et al., 2015; Milan et al., 1996), we also find that the density of cell divisions decreased linearly with time during the developmental process (Fig. 3A).

Epithelial wounding triggers a spatio-temporal reprogramming of cell division

Analysis of wounded tissues reveals striking differences in cell division behaviour when compared to unwounded tissue (compare Fig. 3A with Fig. 3C). These altered behaviours are highly dependent on the size of the wound. For larger wounds (15-20μm radius), there are initially significantly fewer cell divisions (i.e., a lower division density) in the wounded epithelium compared to unwounded tissues (Fig. 3C); this wound-associated inhibition of cell division reaches its low point at 60-70mins post-wounding. In contrast, smaller wounds (8-12μm radius) do not exhibit a similar reduction in cell divisions immediately following wounding (Fig. 3C). However, both small and large wounds exhibit a subsequent and dramatic synchronised burst of cell divisions at 100 min post-wounding, double that of unwounded tissue at the peak of this proliferative surge

(Fig. 3C); after 3 hours post-wounding, the division density of wounded tissue returns to unwounded levels (Fig. 3C). We calculated the space-time correlation for the cell divisions in the wounded tissue and found a similar high spatial correlation around the origin with the same range as unwounded tissue (Fig. S1B-C); nevertheless, the temporal correlation was altered, due to the observed suppression and later synchronisation of divisions caused by wounding.

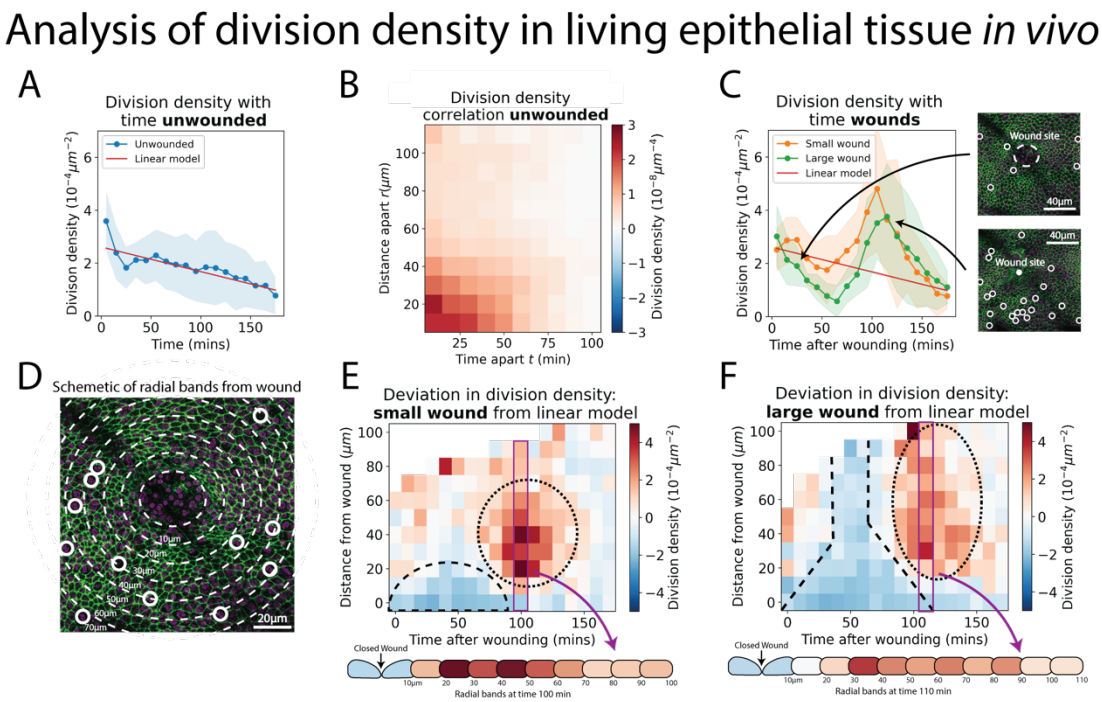

Figure 3. Analysis of cell division density in living epithelial tissue in vivo*. A) The density of cell divisions in the unwounded tissue, with faded blue region showing the standard deviation. The red line is the line of 'best fit' of the unwounded data. B) A heatmap of the division density correlation over distance and time in unwounded epithelial tissue. Red indicates positive, and blue negative correlation. C) The density of cell divisions in the wounded tissue, with either small or large wounds, with faded regions showing associated standard deviation. The red line is the line of best fit of the unwounded data. The micrographs show representative divisions identified at two different time-points post-wounding. D) Diagram of the annular bands around a wound, each 10µm wide (white dashed line); white circles indicate cell divisions. E-F) Heatmaps of the change in division density for small and large wounds compared with a best fit linear model of unwounded data. Red areas have more divisions and blue less than equivalent regions in the unwounded data. The dashed lines highlight areas in which cell divisions decrease and the dotted lines highlight areas in which divisions increase compared to unwounded data. Schematics below the heatmaps in E and F show the radial division densities 100min and 110min after wounding, respectively.*

Since our model also identifies the spatial coordinates of the cell divisions, we can also determine their distance from the wound edge and this enables us to calculate the density of divisions in zones extending out from the wound edge (Fig. 3D). To analyse how the wounded division density varies over space and time, we have compared the wounded division data to that of unwounded tissue (by making a line of best fit for the unwounded data as a linear model and comparing the wounded data to this). This enables us to show the spatial-temporal change in division density in a heatmap, with blue indicating a decrease and red an increase in division density (Fig. 3E-F). For

small wounds, there is clear decrease in divisions extending up to 20μm (approx. 5 cell diameters) back from the wound edge until 70 mins post-wounding. In large wounds, this reduction in division density extends much further back from the wound edge, beyond even the field of view (i.e., greater than 100μm, approx. 25 cell diameters). The subsequent synchronised burst of divisions occurs between 20-70μm back from the edge of small wounds and extends beyond 100μm across the whole field of view for large wounds (Movies S2 and S3).

The orientation of cell divisions might be biased by tissue tension but is not influenced by wounding

In addition to a general analysis of cell division density, we can also use our newly developed Models to quantify the orientation of cell divisions in an automated manner. To achieve this, we developed a second Deep Learning Model called 'U-NetOrientation'. Whilst our earlier model reveals the locations of dividing cells, we modified this algorithm to additionally report division *orientation* using nuclear positioning. To achieve this, the same cell divisions from the previous training videos were used to train the new U-NetCellDivision model. We initially labelled the cell division orientations by hand and then trained the new Deep Learning Model to extract θ i.e., the orientation of the division (see Fig. S2A) (Olenik et al., 2022). After training, we tested the model's accuracy and found that the median error is $4°$ $(\pi/45\ radians)$ (Fig. S2B; Movies S1,S2 and S3).

Following this model training and validation, we used the U-NetCellDivision model to quantify division orientation in unwounded and wounded epithelial tissues (Fig. 4). In the unwounded pupal epithelium, we measured the division orientation relative to the proximal/distal (P/D) axis of the wing (Fig. 4A). Previous work has demonstrated that hinge contraction in the proximal part of the wing causes tension in the wing along the P/D axis (Athilingam et al., 2021b; Etournay et al., 2015), and because of this, we expected to observe a bias of division orientation along this axis. However, conversely, we observe a small orientation bias at 45° to this axis (Fig. 4A). Interestingly, our subsequent analysis revealed that daughter cells undergo later "shuffling" movements to rearrange their positions after cytokinesis so that the *final* daughter cell orientations (using centres of the cell shapes) consistently align along with the P/D axis (Fig. 4B). In order to analyse these 'shuffling' rearrangements, we need to segment and track cell boundaries. However, applying traditional tools, such as the ImageJ Tissue Analyzer plugin (Aigouy et al., 2016; Etournay et al., 2016), we found that our samples were too noisy to analyse without time-consuming manual editing of the segmentation. Hence, we automated this cell boundary segmentation by developing an additional (4th) Deep Learning model to detect cell boundaries (Fig. 2D). Here, we developed a model using multiple focal planes (individual slices of the z-stack) from the confocal imaging data. We used a 3-focal plane input to increase the amount of information available to the model, which we have called U-NetBoundary (Fig. 2D-E). This utilised an algorithm which identifies the most focused plane and the planes above and below it (see Materials and Methods for further details) to provide sufficiently accurate automated identification of cell boundaries. After training, we tested the U-NetBoundary model on 12 images (12,514 cells) and ran the output through ImageJs Tissue Analyzer (Aigouy et al., 2016; Etournay et al., 2016) to utilise the Watershed algorithm. Table

2 shows that using U-NetBoundary leads to a much better dice score and so is more reliable than using a single focal plane without deep learning.

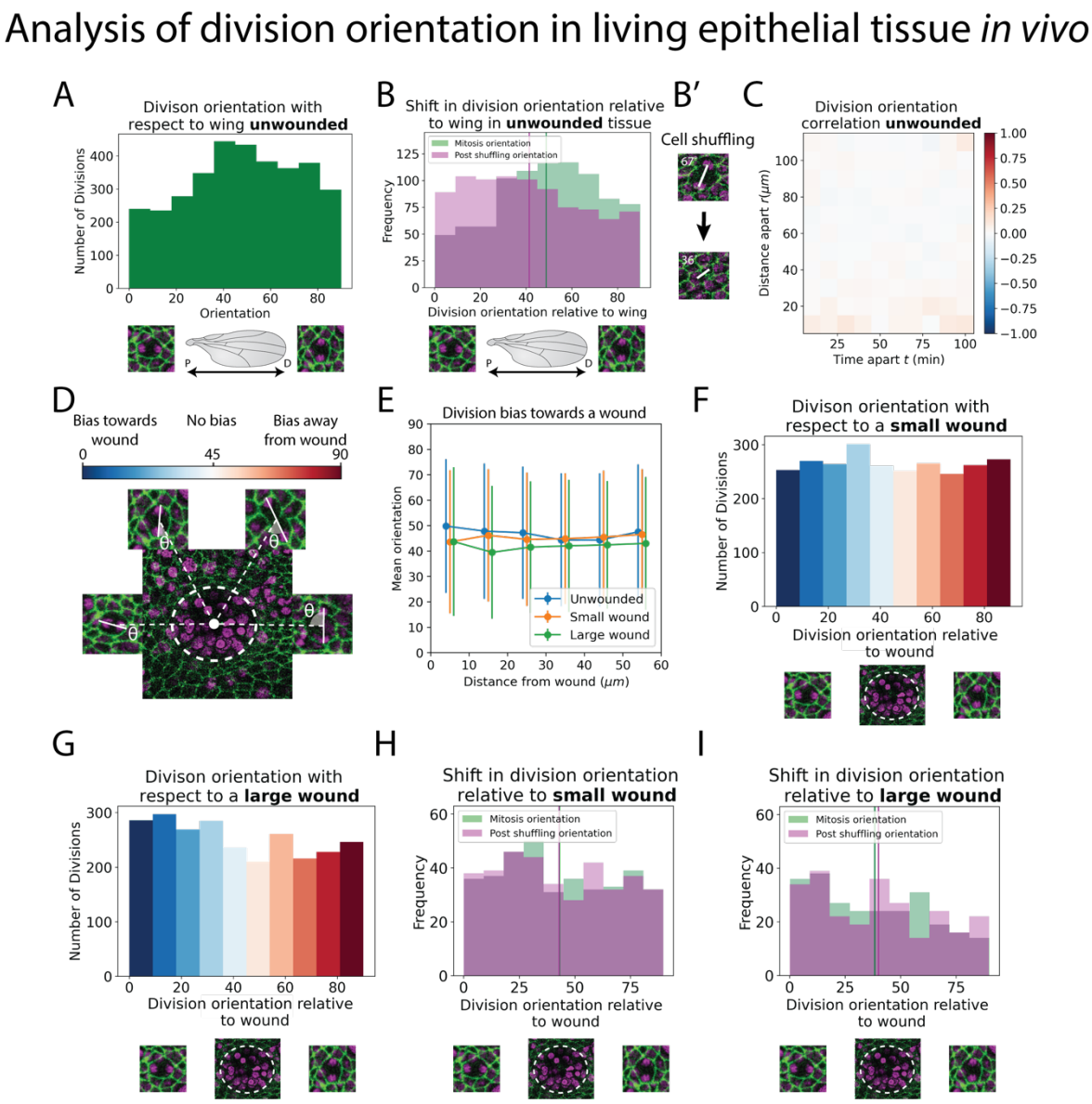

Figure 4. Analysis of division orientation in living epithelial tissue in vivo. *A) Distribution of the division orientations with respect to the proximal-distal axis of the pupal wing in unwounded tissue. Cell division orientations of 0° and 90° are illustrated in the micrographs. B) Distribution of the division orientations with respect to the wing in unwounded tissue (green) and the daughter cell orientations 20 mins after dividing (magenta), with examples of the orientation of division before and after cell shuffling (B'). C) Heatmap of the space-time correlation of division orientation. Red indicates positive correlation, blue negative and white no correlation. D) Diagram of cell division orientation with respect to a wound; lower values are dividing towards the wound and higher values away. E) Mean division orientation towards the wound as a function of distance from wound for small and large wounds. For unwounded tissues an arbitrary point is chosen as a "virtual wound". F-G) Distribution of the division orientations with respect to small and large wounds. The spectrum of colours (same as in D) indicates the bias in orientation towards the wound. H-I) Distribution of the division orientations with respect to the wound in small and large wounds (green), and the daughter cell orientation 20 mins after dividing (magenta).*

Using U-NetBoundary, we are now able to track daughter cells post-division, with the required level of accuracy. Our algorithm automatically filters out any tracks that have large and/or sudden changes in size and shape of daughter cells, which indicates a segmentation mistake (see Methods for details). Once these anomalies have been identified and removed, our data is ready for analysis. To determine whether daughter cell orientation relative to one another changed during cell shuffling (in the period immediately after dividing), we measured the angle of a line drawn between the centre of 2 daughter nuclei 20 mins after cell division (Fig. 4B') to find the change in orientation. We found that on average post-division shuffling shifted final daughter cell orientations by 14.8°. When we measured the post shuffling orientation relative to the wing's P/D axis, we found that the distribution had shifted to acquire a small bias in the direction of the tension in the tissue (Fig. 4B) and the mean orientation relative to the P/D axis had shifted by 8.5°. If cell division orientation is influenced by local tension in a developing tissue, then one might expect that cells about to divide in close proximity to one another will experience similar local forces and so might divide with the same orientation. To examine if this was the case, we measured the correlation between division orientation within space and time, but found no such correlation (Fig. 4C).

Next, we measured division orientation relative to a wound (Fig. 4D-G). Here, the possible range of cell division orientations varies from 0° to 90°, with an orientation of 0° indicating that cells divide towards a wound (radially) and an orientation of 90° indicating cells divide perpendicular to a wound (tangentially). To investigate whether cell division is biased towards a wound, we averaged the orientation of all divisions around the wound. If divisions are biased towards a wound, then their average orientation should be significantly less than 45° (or above 45° if significantly biased away from the wound); conversely, an average bias of 45° would suggest that cells divide in an unbiased manner. Our data suggest a rather random orientation of cell divisions occurs in response to wounding (Fig. 4D-G, Movies S4 and S5). Whilst these data suggest that there is no initial bias in the orientation of cell divisions in the epithelium following wounding, we wondered whether subsequent "shuffling" of daughter cells might be influenced by tissue tensions within the repairing epithelium. We undertook the same tracking of daughter cell movements as described for unwounded tissue (Fig. 4B), but observe no significant shift in the cell orientations post-shuffling; rather, the distribution of post-division orientations is the same as for the divisions themselves (Fig. 4H and 4I), suggesting that the local tension changes triggered by wound healing are not sufficient to have a measurable effect on the orientation of cell divisions, over and above those seen unwounded tissue (Fig. S3).

Discussion

Deep learning is well-suited to detecting variable but specific features in a dense field, for example for face detection in a crowd. Hence, it is particularly useful for identifying patterns in noisy biological or clinical data. A key step with these data is identifying inputs for a given task and this will be somewhat bespoke and dependent on the type of data being analysed. Here, we analyse confocal microscopy movies of translucent three-dimensional epithelial tissue, in order to identify and classify cellular behaviours in space and time during morphogenesis and tissue repair. To this end, we have developed novel Deep Learning tools for identifying and locating when and where cell divisions occur, as well as their division orientation and post-division shuffling behaviour of the daughter cells in unwounded and wounded tissue. This has allowed us to ask quite nuanced questions about cell division behaviours across an epithelial field, as well as investigate how an individual cell division might influence local cell behaviours by its close neighbours.

For such dynamic cell behaviours as cell division, there is a clear need to analyse imaging data from high resolution confocal microscopy movies of living tissue. Because of the vast volume of this data, doing this task manually would not be possible, and so one must develop sophisticated Deep Learning strategies for the analysis. Our approach has been to generalise techniques currently used in computer vision for static images and adapt them to deal with dynamic data. Previous deep learning approaches have considerably improved the accuracy of detection of mitotic indexes in static biopsy sections of clinical tissues for cancer diagnosis (Aubreville et al., 2020; Piansaddhayanaon et al., 2023). Our study is novel in that it extends this type of analysis into *in vivo* tissues and utilises dynamic movie datasets originating from multi-channel 3D z-stacks, rather than still images.

What are the biological findings so far?

Our deep learning tools have enabled us to accurately quantify complex cell behaviours – such as cell divisions and subsequent daughter cell rearrangements - from large datasets which, in turn, has revealed trends that are otherwise hidden within the biology. Previous studies of wound healing in mammalian models have suggested that cell migration and cell division largely occur in separate epidermal domains following wounding (Aragona et al., 2017; Park et al., 2017) and our data support this. Our large wounds show a clear reduction in cell divisions, below pre-wound levels, in cells close to the leading epidermal wound edge where cells are actively migrating. Nevertheless, our data suggest that cell migration is not absolutely dependent on this “shut down” in divisions because we see no observable cessation of cell division around small wounds as they are closing. For both large and small wounds, we observe a synchronised proliferative surge of cell divisions commencing 60 mins post-wounding (and peaking shortly afterwards) but this is restricted to a domain beginning ~5 cell diameters back from the leading edge. These divisions are unlikely to be a major driver of wound closure because the rate of wound closure is the same before and after the proliferative surge; indeed, cell divisions at the leading edge have largely halted during the

most dramatic closure period. However, these cell divisions are likely to be a consequence of wounding and the additional cells will help repopulate the tissue to restore near original numbers of epithelial cells and return tissue structure (and tensions) to pre-wound levels. This synchronised surge in cell proliferation in a band of cells back from the leading edge (to levels that are twice background levels for unwounded tissue) is potentially related to our observation of a strong correlation in the timing of cell divisions by close neighbours in unwounded epithelial tissue. Such a "community effect" might be mediated by short-range chemical signals or local mechanical signals that operate locally in unwounded tissues and are recapitulated and expanded following wounding.

Once a cell has received signals driving it to divide, how do tissue tensions influence the orientation of this cell division in the unwounded or wounded epithelium? Previous studies of cells adjacent to the segmental boundaries in the *Drosophila* embryo show how local tissue tensions, driven by contractile actomyosin cables, can orient the plane of cell divisions adjacent to these boundaries (Scarpa et al., 2018). Moreover, analyses of experimentally stretched Xenopus tissue revealed that whilst global cell division rates are regulated by tissue-level mechanical stress, division orientation is controlled more locally by cell shape(Nestor-Bergmann et al., 2019). In our studies, we observe cells dividing with no specific orientation bias along the global P/D axis; however, subsequently, we do see the resulting daughter cells shuffle to adopt an alignment more biased along this P/D tension axis. Surprisingly, we see no apparent bias in orientation of cell divisions following wounding; this is unexpected as one might presume there to be considerable tissue tension changes in the vicinity of a wound (Guzmán-Herrera & Mao, 2020; Scarpa et al., 2018). However, this effect might be partially explained by our observation that most cell divisions are distant from the main source of changing wound tensions, the contractile actomyosin purse-string that rapidly assembles in the leading epithelial wound edge cells (Tetley et al., 2019; Wood et al., 2002), and that these divisions occur largely after the wound has closed. One further possibility is that local mechanical feedback signals may lead a dividing cell to have division orientation counter to its recently divided neighbour in order to equilibrate tissue tensions.

To further extend these studies and to gain a more comprehensive understanding of how different cell behaviours, particularly beyond those directly related to cell division, coordinate in a repairing tissue, additional development of our deep learning algorithms might be useful to extract more information from the time-lapse imaging data. For example, this might enable us to correlate changes in the density or orientation of cell divisions at the wound site, with other contributing cell behaviours (such as cell shape changes and cell intercalations). Similarly, it would be possible to integrate our analyses of cell behaviour with tools that enable live-imaging of wound-induced signalling (e.g. calcium signalling at the wound edge using calcium sensitive GCaMP transgenic reporters), in order to determine how such signalling pathways might be integrating the various wound repair cell behaviours following injury.

Future directions for our deep learning approaches

In this study, we have converted a suite of image classifiers (ResNets) into U-Net via the Dynamic UNET function from the fast.ai library. To analyse cell divisions in *Drosophila* pupal tissues we extended the dimension of the data being analysed to include multiple time steps in order to identify the dynamic features associated with individual cell division events. To achieve this, we have modified the architecture of these models by increasing the feature inputs in the first layer. With tweaks the model can provide us with additional, but related, outputs, for example, detection of defective cell divisions which might be relevant in studies of oogenesis or cancer. Our algorithms could also be extended further by altering the initial layers of the model; this would enable generation of models which are able to identify much more complex dynamical features. Indeed, a major challenge is to generate AI (or Deep Learning) models that can be adapted to identify cellular (or pathological) features across a broad range of tissue types and in data generated through a range of different imaging modalities. The tissue employed in our current study was a relatively flat 3D epithelium with few other cell lineages present in the microscopy data (only migratory immune cells), but such AI approaches could be expanded to cater for mixed populations of cells existing in larger 3D volumes, for example gastruloids or even whole embryos as they develop and undergo morphogenesis, or to study other complex cell:cell interactions or movements e.g. immune cell interactions or flagella beating. With any such new methodology there will be much interesting work to come, in optimising movie time resolution and model depth.

The development of the next generation of *realistic* theoretical models of tissue mechanics during morphogenesis and repair (and other physiological episodes such as cancer progression) in vivo, will require dealing with increasingly large and complex imaging datasets. To extract information from them will require the use of further deep learning tools to automate the process of data extraction (of e.g. cell velocities, cell shapes and cell divisions). The theories that must be developed will be statistical mechanical (stochastic) in nature and identifying the relevant degrees of freedom and microscopic dynamics as well as quantifying the fluctuations will be highly challenging. We envision promising approaches will include (1) inferring equations of motion based on optimising the parameters of PDEs for continuum fields (e.g., nematic director fields for cell orientations) using deep learning (Colen et al., 2021) or (2) reverse engineering the dynamics based on spatiotemporal correlation functions (of e.g. cell shapes and cell velocities) that deep learning tools can elucidate. An advantage of the second approach is that one can also estimate the scale of fluctuations in the system.

The novel deep learning models that we present here are able to identify cell divisions and their orientations (as well as subsequent orientations of daughter cells) in dynamic movie data with high accuracy. We anticipate our models will have broad application and enable similar analysis of tissues where cell nuclei and/or membranes have been labelled, and to facilitate this we have made a napari plugin that can run each of our models (all of which can be found at https://github.com/turleyjm/cell-division-dl-plugin). Ultimately, we envisage that

such deep learning approaches are a first step towards development of AI tools for analysing dynamic cell behaviours, including cell divisions, in complex physiological as well as pathological processes occurring in a variety of organisms and tissue types.

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Competing interests

The authors declare that they have no competing financial interests.

Author contributions

J.T. designed and conducted the experiments. T.L, I.C. P.M. and H.W. designed the study, coordinated the project and, together with J.T., wrote the manuscript.

Materials and Methods

Drosophila Stocks and Husbandry

Drosophila stocks were raised and maintained on Iberian food according to standard protocols (Greenspan, 1997). All crosses were performed at 25°C. The following *Drosophila* stocks were used: *E-cadherin-GFP* and *Histone2-RFP* (BDSC stock numbers #60584 and #23651, respectively, obtained from the Bloomington *Drosophila* Stock Centre, Indiana).

Confocal Imaging and Data Processing

Drosophila pupae were aged to 18h APF at 25°C. Dissection, imaging, and wounding were all performed as previously described (Weavers et al., 2018). The time-lapse movies were generated using a SP8 Leica confocal. Each slice of the Z-stacks consisted of a 123.26 x 123.26μm image (512 x 512 pixels) with a slice taken every 0.75μm. The z-stacks were converted to 2D using our own python version of the ImageJ plugin stack focuser (Umorin, 2002). Images were taken every 2mins for 93 timepoints (just over 3 hours of imaging). The data was manually labelled by making a database of the locations in space and time of the divisions and their orientations.

From the 93 frame full videos, we extracted 5 sequential timepoints to make a video clip (10 frames encompassing 2 different channels) or 3 timepoints and frames (for the U-NetCellDivision3). This was performed 89 times (one for each timepoint, apart from the last 4 timepoints). Our training data thus consisted of 979 video clips (11 full videos), our validation data consisted of 356 video clips (4 full videos) and our testing data consisted of 445 video clips (5 full videos). There are 4206 divisions across all the videos (on average there are 2.38 divisions in each clip). We define the moment in time a division occurred as the last timepoint of metaphase before anaphase starts. For each clip, we make a corresponding output mask (also 512 x 512 pixels) with divisions labelled with a white circle. This is generated using our hand labelled database, which has the information about each divisions location in space and time. These video clips (plus their corresponding output masks) are the labelled data that will be used for training the U-NetCellDivision deep learning models.

For calculating the orientation of cell divisions, we used the 10 frame video clips. For each division, we made a cropped video clip that was a 14.4 x 14.4μm square box around the centre of a division. The images in the cropped video where 60 x 60 pixels (which we rescaled to 120 x 120 as this improved the performance of the models). The same training dataset that was used for training the U-NetCellDivision models were used for U-NetOrientation, with 2,638 cropped video clips from the 11 full videos. The validation data was 660 cropped video clips from 4 full videos and testing had 1135 cropped clips from 5 full videos. The output for the model is an oval elongated in the same orientation as the division. The oval has radius of 50 pixels in the long axis and 15 in the short axis. In the labelled data, each division's orientation

was measured by hand and the corresponding oval mask was generated. The mask is also 120 x 120 pixels.

For detecting cell boundaries, we maximise the information supplied to the model by using a modified stack focuser which identifies the most 'in focus' pixels in a stack. Our version also outputs the pixels above and below the most in focus pixel and records this as an RGB image with colours corresponding to above (R), focused (G) and below (B) pixels; the model will learn to use these upper and lower colours to identify if there is a genuine cell boundary or if focused pixels are just noise within the image. We also rescaled our images from 512 x 512 pixels to 1024 x 1024 pixels, to increase the width of the boundaries so that they are large enough for the model to learn to detect them. The data was segmented using Tissue Analyzer (Aigouy et al., 2016; Etournay et al., 2016) to apply the Watershed algorithm on the original single focal plane data (then correcting by hand the boundaries on 59 images, finding a total of 58582 cells). The boundaries are 1 pixel in width in the output labelled masks. To give the model a wider target to reproduce we eroded the image to make the boundaries 3 pixels wide. As we have increased the scale of the images this is around the same pixel thickness as the boundaries in the input.

Network architecture

We converted a Resnet34 model into a U-Net architecture via the Dynamic UNET function from the fast.ai library (He et al., 2016b; Howard & others, 2018; Ronneberger et al., 2015). The weights from the Resnet 34 classifier were used to take advantage of transfer learning (Howard & Gugger, 2020). For the second version of the model (U-NetCellDivision10), the first layer of the model was replaced with a Conv2d layer with 10 features in and 64 out. The inputs to the model were 512 x 512 x 3, or, 10 x 512 x 512 voxels for U-NetCellDivision3 or U-NetCellDivision10, respectively. The U-NetOrientation has the same architecture as U-NetCellDivision10, but takes 10 x 120 x 120 videos as inputs. For U-NetBoundary we used the Resnet 101 classifier and converted it into a U-Net with Dynamic UNET function. This model has inputs of 1024 x 1024 x 3. Source code is available at https://github.com/turleyjm/cell-division-dl-plugin.

Data augmentation

The data were augmented using the albumentations library (Buslaev et al., 2020). The transforms used were Rotate, HorizontalFlip, VerticalFlip, GaussianBlur, RandomBrightnessContrast and Sharpen.

Training models

Training our deep learning models requires that we spilt the data into 3 separate groups (Howard & Gugger, 2020): 1) Training data: this is data from which the model directly learns (in this instance, the 11 videos described above); 2) Validation data: this data is used to test

the model during the training process, to validate whether the algorithm is learning the patterns correctly and if it is able to perform on (similar but) unfamiliar videos. This ensures that the model hasn't simply "remembered" the 'answer' in the training data (over-fitting); 3) Testing data: once we have fully trained the model, we run a final dataset through the model as our ultimate test of the algorithm (see Table 1 and 2). Paperspace's gradient ML Platform was used for training the models. The machine used was one with NVIDIA Quadra P5000 or P6000 GPU. We trained using an Adam optimization.

Detecting divisions from U-NetCellDivision outputs

After running a full video through our model in individual video clips, we have output masks with white circles in the same locations as the divisions (see Fig. 2A and 2B). We detect the white circles using a Laplacian of Gaussian Filter (Kong et al., 2013). The deep learning model is very accurate at finding divisions when they occur, but sometimes mistakenly detects them a frame before and/or after the actual division happens. This is not really surprising as the video clips still look similar after being shifted by one timepoint. The white circles in the frames before and after are normally not as intense as the timepoint of the division, reflecting the weaker confidence of the model in identifying them. To ensure we don't double count divisions, these are suppressed with the brightest circle taken as the timepoint when a cell divides. We have built in some tolerance into our evaluation of the model. In the cases where the algorithm detects one of these divisions and has a brighter spot in a timepoint +/- 1 frame of our labelled data, we still count this as a correctly detected division.

Orientation from U-NetOrientation outputs

To determine the orientation of the oval shape produced by the U-NetOrientation deep learning model, we calculated a second-rank tensor (which we call the q-tensor) for the output image that stores information about the orientation of the oval shapes (Olenik et al., 2022).

$$\boldsymbol{q} = \frac{1}{A^2} \int_A \begin{pmatrix} \frac{1}{2}(x^2 - y^2) & xy \\ xy & \frac{1}{2}(y^2 - x^2) \end{pmatrix} dA$$

Where A is the area of the image and $dA = dxdy$. $\boldsymbol{q}$ can be rewritten as

$$\boldsymbol{q} = q_0 \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{pmatrix}$$

Where θ is the orientation of the shape. To calculate the orientation of a division, we apply these equations to our output image from U-NetOrientation and extract θ.

Using Tissue Analzyer for segmentation

We use the watershed algorithm from Tissue Analzyer (Aigouy et al., 2016; Etournay et al., 2016) which is a plugin for ImageJ for segmentation both from the single focal plane data and from the output of the deep learning U-NetBoundary model. The "Detect bonds V3" function was used to perform the segmentation. We found individual optimised settings for both single focal plane and U-NetBoundary output images. These were not the same settings, as the images are very different. To track cells after segmentation we used the "Track cell (static tissue)" algorithm. The U-NetBoundary outputs are resized back to 512x512 before being run through Tissue Analyzer.

How to adapt this method for other cell division datasets

The models we have developed (optimised for *Drosophila* pupal wing epithelia) can be used on datasets from other systems. To be effective on a new tissue type, re-training will often be needed. In our GitHub repository we include the scripts for training new models https://github.com/turleyjm/cell-division-dl-plugin. For best results, the user should load our model and weights, then train the model from this starting point (called transfer learning (Howard & Gugger, 2020)). The user will also need to generate labelled data (as done in the "Imaging and data processing" section). Once this has been done, the user can utilise the training scripts to teach the model.

Wound, division density and orientation measurements

The epithelial wound was located using the 2D focused E-cadherin channel. The ImageJ plugin Trainable Weka Segmentation (a machine learning algorithm) is trained to find areas of the images that are tissue or non-tissue. Non-tissue could be either a wound or parts of the tissue that are above or below our frame of reference. The tissue/non-tissue binary masks are then hand-edited to remove errors (mostly around the edges of wounds where the images are particularly noisy due to debris). To calculate the division density, we sum the number of cell divisions divided by the area of tissue during a defined period of time. We find the number of divisions from our deep learning model and using the tissue/non-tissue binary masks, we know the area of tissue observed in the video. For measuring division density in relation to a wound, the mask could then be used to extract the wound. We then calculated the distance from the edge of a wound to the divisions using a distance transform (Fabbri et al., 2008). Now we can find all the divisions in a band of a given radius and width. To quantify the density of divisions, we divide the number of divisions by the area of the band. Using both the distance transform and our tissue mask, we can work out the area of the tissue that is in each band. Once the wound has closed, we can no longer perform a distance transform using the wound edge, so we instead take the centre of the last timepoint before the wound closes. This point is the wound site and is where we take our distance transform from. As the tissue is still developing and moving, we track this point over time.

We track the tissue using the ImageJ plugin TrackMate (Tinevez et al., 2017), which tracks the nuclei of cells as they move together in the tissue. Unlike the mitotic nuclei these nuclei are

slow moving so trackable using a non-AI algorithm. By calculating the average velocity of the cells around the wound site, we can track this point and use this as our frame of reference to measure distance from the wound site. The same method is used for unwounded tissue where we chose an arbitrary point as a "virtual wound" which will flow with the local tissue. The starting point for the unwounded tissue is the centre of the image. This gives us our reference point to identify the bands we use for calculating the division density. We measure the orientation of division relative to the centroid of the polygon approximating the boundary of a wound (which we call the wound centre). The difference in angle between the vector from the wound centre to divisions and nomadic division vector is defined as the division orientation. Once the wound is closed the wound centre point was used ,whereas for the unwounded tissue, we used the "virtual wound".

Division density correlation function

We calculate the division density in our system as follows: we image a 123.26 x 123.26µm section of the tissue for 186 minutes taking an image every 2 minutes. This video is converted into a 3D (x,y,t) matrix of dimensions 124 x 124 x 89, whose components are 1 where there is a division and 0 otherwise. Thus, each component represents a 1 μm^2-2 min space-time slice. We defined the time of division as the moment that anaphase starts. We use only 89 (and not all 93) time slices because we have incomplete information about division at the beginning and end of the video.

We number each of the elements in the matrix $i \in [1, \dots, N]$ where $N = 1{,}368{,}464$ is the number of elements. For the ith element, we define the *mean mitosis density*, $M^i(t, r)$, to be the division density in a space-time annular tube spatially centred at the point corresponding to the ith element, with spatial radius $(r - \delta r, r]$; temporally, the annular tube is of extent $(T - t, T - t + \delta t]$. Here, T is the time corresponding to the ith element, δr is 10µm and δt is 10 minutes; this is the size of our bins. Consequently, M^i is defined for t = 10, 20 etc min and similarly for r=10, 20 etc µm. When calculating the density of a tube we take the number of divisions in the region and divide by the space-time volume, but we need to take into account the fact that often the annular tube will extend outside the microscope view. Therefore, we divide only by the volume that can be observed using the confocal. It is convenient to extend the definition of mean mitosis density also to t=0 and r =0. When t=0, the annular tube has no temporal depth and is concerned only with the time T. Similarly, when r=0, the annular tube becomes a line. When both are 0, the annular tube becomes a single point in space time. We define $M^i(0,0)$=1 if the ith element is a division and $M^i(0,0)$=0 otherwise.

We define the correlations between the divisions as:

$$\langle M(0,0)M(t,r)\rangle_c = \langle M(0,0)M(t,r)\rangle - \langle M(0,0)\rangle\langle M(t,r)\rangle$$

The first term on the RHS is

$$\langle M(0,0)M(t,r)\rangle = \frac{1}{N}\sum_{i}^{N} M^i(0,0)M^i(t,r) = \frac{1}{N}\sum_{i\in d} M^i(t,r),$$

Where d is the subset of elements where $M^i(0,0) = 1$, i.e., corresponds to a division. This means that this term is looking only at the densities around the divisions. The second term is

$$\langle M(0,0)\rangle = \frac{1}{N}\sum_{i}^{N} M^i(0,0) = \frac{N_d}{N},$$

where N_d is the number of divisions in the video. The last term is

$$\langle M(t,r)\rangle = \frac{1}{N}\sum_{i}^{N} M^i(t,r) \approx \frac{1}{N_R}\sum_{i\in R} M^i(t,r).$$

Here, since the computation would take an extremely long time as there are $N = 1{,}368{,}464$ elements, we approximate it by randomly choosing a subset, R, of N_R=1000 elements.

The resulting division density correlation function (Fig. 3B) shows that there is a positive correlation in space and time, so $\langle M(0,0)M(t,r)\rangle > \langle M(0,0)\rangle\langle M(t,r)\rangle$ for $r < 40\mu\mathrm{m}$ and $t < 50$. This means that if we find one mitotic event we are more likely to find others nearby and soon afterwards.

Division orientation correlation function

We compute the orientation angle of each division using U-NetOrientation, and form the orientation vector:

$$\boldsymbol{p}(\theta) = \begin{pmatrix}\cos 2\theta \\ \sin 2\theta\end{pmatrix}.$$

Here, 2θ is used since cell division orientation is nematic and we need $\boldsymbol{p}(\theta) = \boldsymbol{p}(\theta + \pi)$. To compare two division orientations, we take the dot product of the orientation vectors: 1 indicates that the divisions are aligned, -1 that they are perpendicular, and 0 that their orientations differ by $\pi/4$.

The division orientation correlation function is defined as,

$$T(t,r) = \langle \boldsymbol{p_i}\cdot\boldsymbol{p_j}\rangle$$

Where $\langle \boldsymbol{p_i}\cdot\boldsymbol{p_j}\rangle$ is the mean dot product comparing the orientation of every pair of divisions within a radius $(r-\delta r, r]$ and $(t-\delta t, t]$ time from each other. This is calculated as explained above and shown in Fig. 4C. Values of $T(t,r)$ close to 1 indicate highly aliened divisions, 0 no correlation and -1 anti-correlated.

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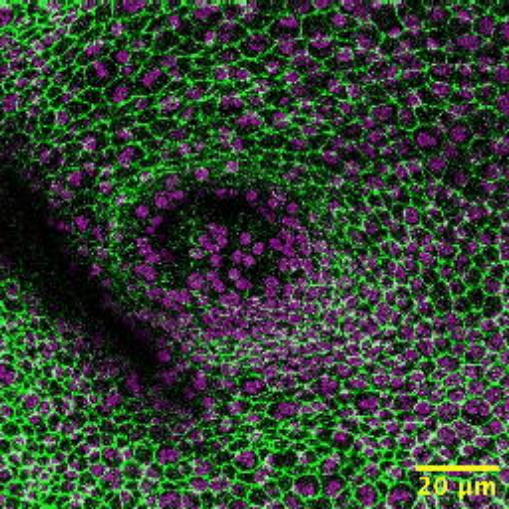
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