inTRACKtive — A Web-Based Tool for Interactive Cell Tracking Visualization

Teun A.P.M. Huijben[a], Ashley G. Anderson III[b], Andrew Sweet[b], Erin Hoops[b], Connor Larsen[b], Kyle Awayan[a], Jordão Bragantini[a], Chi-Li Chiu[b], Loïc A. Royer[a]

[a] Chan Zuckerberg Biohub, San Francisco, United States
[b] Chan Zuckerberg Initiative, Redwood City, United States

correspondence to teun.huijben@czbiohub.org, loic.royer@czbiohub.org

We introduce inTRACKtive, an innovative web-based tool for interactive visualization and sharing of large 3D cell tracking datasets, eliminating the need for software installations or data downloads. Built with modern web technologies, inTRACKtive enables researchers to explore cell-tracking results from terabyte-scale microscopy data, conduct virtual fate-mapping experiments, and share these results via simple hyperlinks. The platform powers the Virtual Embryo Zoo, an online resource showcasing cell tracking datasets from state-of-the-art light-sheet embryonic microscopy of six model organisms. inTRACKtive's open-source code allows users to visualize their own data or host customized viewer instances. By providing easy access to complex tracking datasets, inTRACKtive offers a versatile, interactive, collaborative tool for developmental biology.

The field of developmental biology is undergoing a profound transformation, driven by groundbreaking advances across multiple disciplines.[1] In particular, the convergence of state-of-the-art light-sheet microscopy and cutting-edge image analysis algorithms is redefining our ability to study and understand embryogenesis *in vivo*.[2] Light-sheet microscopy enables rapid, large-scale, multicolor imaging of developing embryos in unprecedented detail, allowing scientists to capture dynamic processes as they unfold in real-time.[3–5] Simultaneously, the advent of advanced cell tracking technologies, such as Ultrack,[6] Linajea,[7,8] Elephant,[9] TGMM,[10] Trackmate,[11] and TrackAstra,[12] has made it possible to follow individual cells throughout embryonic development with remarkable precision and speed.[13] These innovations, which have emerged in the past decade, are only now realizing their full potential, offering the capability to track almost all cells in an embryo, from the earliest stages of development to fully gastrulated embryos. This unprecedented level of detail opens the door to answering fundamental questions about tissue development, organ formation, and the intricate orchestration of the cell behaviors that govern the entire embryo.[14,15]

However, the size and complexity of these microscopy datasets — often reaching tens of terabytes and containing up to tens of thousands of cells across hundreds of time points — pose significant challenges. While these datasets hold the potential to reveal novel biological insights, accessing and interacting with such complex data typically demands highly specialized technical expertise and substantial computational resources. Consequently, only a limited subset of researchers can fully leverage these data, creating a barrier to broader adoption. Could a more user-friendly solution be developed that enables researchers to explore and analyze these datasets, regardless of their computational expertise or available hardware?

We introduce inTRACKtive, an innovative web-based tool designed to address this challenge by providing an intuitive platform for visualizing and interacting with large 2D and 3D cell tracking datasets. With inTRACKtive, users can seamlessly explore large tracking datasets, selecting specific cells or groups of cells and tracing their lineages in an interactive, three-dimensional environment (see Fig. 1a-b and Supplementary Video 1). The platform operates entirely in a web browser, requiring no software installation or manual data downloads, making it easily accessible to any user. In addition, users can share their exact viewing configuration - complete with view settings, zoom levels, and selected cells - simply by sharing a link, allowing for effortless collaboration and dissemination of results.

We used inTRACKtive to create the Virtual Embryo Zoo (embryozoo.org), a comprehensive online resource that showcases the highest-quality tracked light-sheet microscopy datasets of developing embryos (Fig. 1c and Supplementary Video 2). This platform allows researchers to investigate the early embryogenesis of six widely studied model organisms (Table 1), Drosophila,[10] zebrafish,[15] C. elegans,[16] Ascidian,[17] mouse,[4] and Tribolium[18] — via an intuitive web-based interface. Not only can users visualize these datasets, but they can also download the complete tracking data, which can be easily imported into *napari* for further analysis. In addition, the Virtual Embryo Zoo offers researchers the opportunity to contribute and showcase their own datasets (Fig. 1d), with the vision of creating a growing collaborative resource for the community.

Technically, inTRACKtive is built using modern web

technologies, including TypeScript, React, and three.js, with Vite as the bundler and Vercel for deployment. The platform is optimized for performance, allowing users to interact with large-scale datasets. The app runs entirely client-side and only relies on static hosting for both the application and data. This makes it easy and inexpensive to self-host the application and make your own data accessible. One key innovation is the use of a specialized cell tracking format based on Zarr,[19] which enables asynchronous, lazy data loading. This ensures that tracking results from large imaging datasets can be explored seamlessly without significant delays or computational overhead. The tool works in any browser and including those on tablets and smartphones, offering flexibility in how users interact with the data.

Looking ahead, there is potential to expand inTRACKtive's capabilities. One exciting possibility is the incorporation of imaging data alongside cell tracking results. Another area for development is further customization of track visualization, such as grouping or coloring tracks based on cell type, size, or gene expression. While this functionality is not yet available directly in inTRACKtive, the platform allows the export of a user-selected subset of data that can be further analyzed and visualized in tools like *napari*, where such features already exist. Thus, inTRACKtive serves as an ideal platform for sharing and disseminating complex cell tracking results, combining ease of use with the flexibility to integrate with more specialized software for advanced analyses.

In summary, inTRACKtive offers a powerful, versatile tool for the interactive visualization of cell tracking data, eliminating the need for complex software installations or large data downloads. Beyond visualization, inTRACKtive enables users to select individual cells, trace their lineages, and investigate both their ancestors and descendants, facilitating deeper insights into developmental processes. The platform serves multiple use cases: as a gateway for exploring datasets in the Virtual Embryo Zoo, as a tool for visualizing a researcher's own cell tracking data (easily shared via a link), and as a customizable viewer for users who want to host their own instances. Conversion scripts for exporting cell tracking results into the Zarr format used by inTRACKtive are provided.

Importantly, inTRACKtive is freely available and open-source (github.com/royerlab/inTRACKtive). By enabling the creation of the Virtual Embryo Zoo, inTRACKtive has the potential to become a valuable resource to the cell and developmental biology community and beyond, offering a unique, browser-based playground for interacting with state-of-the-art microscopy tracking datasets.

Supplementary Videos

1. inTRACKtive web-viewer;
2. Virtual Embryo Zoo website;

Data availability statement

The tracking data presented in this study is available for download from the Virtual Embryo Zoo website (embryozoo.org). The datasets are either sourced from the original authors or tracked by us using the Ultrack[6,20] algorithm (see Table 1). All data has been converted and normalized to a common format compatible with inTRACKtive and *napari*, ensuring seamless interaction and visualization.

Code availability statement

The repository for inTRACKtive, including documentation, examples code, and videos, can be found at github.com/royerlab/inTRACKtive.

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Author Contributions

J.B. and L.A.R. conceived the research. A.A., A.S., E.H, C.L. and C-L.C developed the initial version of inTRACKtive. T.A.P.M.H. collected the light-sheet datasets from the original authors, converted them into the applicable formats, and further developed inTRACKtive (guided by A.A. and A.S.). J.B. performed tracking of the Tribolium and Zebrafish data using Ultrack. K.A. and T.A.P.M.H. built the Virtual Embryo Zoo website. T.A.P.M.H. and L.A.R. wrote the paper. T.A.P.M.H. led the project. L.A.R. supervised the research. All authors contributed to editing the manuscript.

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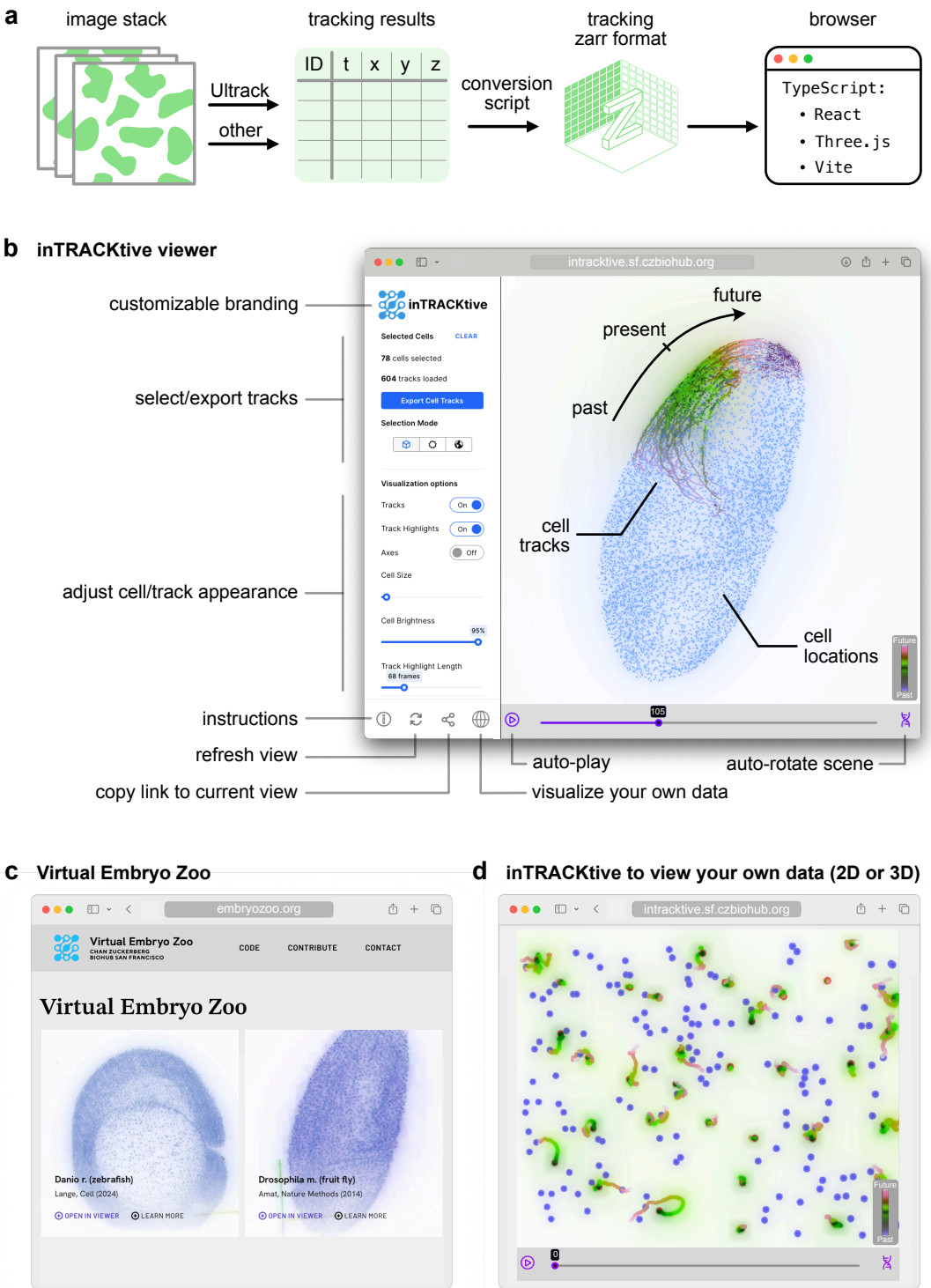

Fig. 1 | inTRACKtive cell tracking viewer and it's applications. a inTRACKtive data pipeline. After users track their datasets with their preferred cell tracking software, the tracking results are converted to our custom Zarr format using a provided conversion script, and can be interactively visualized in the web-base tool. **b** The inTRACKtive web-viewer of cell tracking results. Users can upload their own data, select cells of interest, trace their lineages, adjust the appearance of the cells and tracks, and copy the state of the viewer into a sharable link. **c**, The Virtual Embryo Zoo encompasses six light-sheet microscopy datasets of developing embryos. The website provides a video graphical overview of the datasets, with one-click access to inTRACKtive viewer for visualizing the cell tracking data (see **b**) and the details of the data (paper, organism, authors, tracking algorithm, etc.). **d** inTRACKtive can be used to visualize ones own 2D or 3D cell tracking data in the browser.

Dataset	Paper	Tracking
Danio r. (zebrafish)	M. Lange, *in press* (2024)[15]	Ultrack[6,20]
Drosophila m. (fruit fly)	F. Amat, *Nature Methods* (2014)[10]	TGMM[10]
Mus m. (mouse)	K. McDole, *Cell* (2018)[4]	Linajea[7,8]
Phallusia m. (sea squirt)	L. Guignard, *Science* (2020)[17]	Astec[17]
C. elegans (worm)	M.W. Moyle, *Nature* (2021)[16]	Linajea[7,8]
Tribolium c. (beetle)	A. Jain, (2018)[18]	Ultrack[6,20]

Table 1 | Details of the six embryo datasets portrayed in the Virtual Embryo Zoo.

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