

Reporting Summary

Nature Research wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Research policies, see our [Editorial Policies](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a Confirmed

- | | | |
|-------------------------------------|-------------------------------------|--|
| ☐ | ☒ | The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement |
| ☐ | ☒ | A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly |
| ☐ | ☒ | The statistical test(s) used AND whether they are one- or two-sided
<i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i> |
| ☐ | ☒ | A description of all covariates tested |
| ☐ | ☒ | A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons |
| ☐ | ☒ | A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals) |
| ☐ | ☒ | For null hypothesis testing, the test statistic (e.g. F , t , r) with confidence intervals, effect sizes, degrees of freedom and P value noted
<i>Give P values as exact values whenever suitable.</i> |
| ☒ | ☐ | For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings |
| ☒ | ☐ | For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes |
| ☒ | ☐ | Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated |

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection

The code used for recording the experiments regarding kinematic replay is available in a public GitHub repository: <https://github.com/NeLy-EPFL/SeptaCam.git>

Data analysis

The code for all analysis was written in Python 3 and is available for editors and reviewers as a CodeOcean capsule. Furthermore, it is available in a public GitHub repository along with a full description of use. <https://github.com/NeLy-EPFL/NeuroMechFly>
Documentation of the code can be also found at <https://nely-epfl.github.io/NeuroMechFly>

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

Data for tethered walking is available at <https://doi.org/10.7910/DVN/Y3TAEC>. Data for tethered grooming is available at <https://dataverse.harvard.edu/dataverse/DeepFly3D>

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☒ Life sciences ☐ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://www.nature.com/documents/nr-reporting-summary-flat.pdf)

Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	No sample size calculation was performed. The estimations obtained from the physics engine in our simulations don't depend on the number of examples. We run several experiments to verify the consistency of the results. Population sizes for optimization were determined empirically and chosen to have a reasonable computation time (maximum 24 h per run).
Data exclusions	Unclassifiable behaviors were excluded for error analysis. We focused on walking or grooming.
Replication	The simulation has been run numerous times on different computers and on different operating systems. We consistently replicated our results.
Randomization	Randomization was not relevant for our study since we do not have experimental groups. We describe a neuromechanical framework and its usability. However, the wild-type animals used in our kinematic replay experiments were randomly chosen.
Blinding	Blinding was not relevant for our study because we are presenting a neuromechanical modeling framework. We only have wild-type animals which are, in principle, indistinguishable from each other.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems		Methods	
n/a	Involved in the study	n/a	Involved in the study
☒	☐ Antibodies	☒	☐ ChIP-seq
☒	☐ Eukaryotic cell lines	☒	☐ Flow cytometry
☒	☐ Palaeontology and archaeology	☒	☐ MRI-based neuroimaging
☐	☒ Animals and other organisms		
☒	☐ Human research participants		
☒	☐ Clinical data		
☒	☐ Dual use research of concern		

Animals and other organisms

Policy information about [studies involving animals](#); [ARRIVE guidelines](#) recommended for reporting animal research

Laboratory animals	Wild-type <i>Drosophila melanogaster</i> female flies were used. They were raised at 25°C on a 12 h light/dark cycle and tested at 2-4 days post-eclosion.
Wild animals	No wild animals were used in this study.
Field-collected samples	No field-collected samples were used in this study.
Ethics oversight	<i>Drosophila melanogaster</i> studies were performed in accordance with an institutional authorization by Swiss national authorities (A120851-21)

Note that full information on the approval of the study protocol must also be provided in the manuscript.