KielMAT: Kiel Motion Analysis Toolbox - An Open-Source Python Toolbox for Analyzing Neurological Motion Data from Various Recording Modalities

Masoud Abedinifar [*,1], **Julius Welzel** [†,1], **Clint Hansen** [1], **Walter Maetzler** [1], **and Robbin Romijnders** [1¶]

1 Neurogeriatrics, Department of Neurology, University Hospital Schleswig-Holstein (USKH), Kiel Germany ¶ Corresponding author

DOI: 10.xxxxxx/draft

Software

- Review
- Repository
- Archive

Editor: Kevin M. Moerman

Reviewers:

- @aaa34169
- @davidpagnon

Submitted: 12 April 2024
Published: unpublished

Summary

The Kiel Motion Analysis Toolbox (KielMAT) is an open-source Python-based toolbox designed for processing human motion data, following open-science practices. KielMAT offers a range of algorithms for the processing of motion data in neuroscience and biomechanics and currently includes implementations for gait sequence detection, initial contact detection, physical activity monitoring, sit to stand and stand to sit detection algorithms. These algorithms aid in identifying patterns in human motion data on different time scales. The KielMAT is versatile in accepting motion data from various recording modalities, including IMUs that provide acceleration data from specific body locations such as the pelvis or wrist. This flexibility allows researchers to analyze data captured using different hardware setups, ensuring broad applicability across studies. Some of the toolbox algorithms have been developed and validated in clinical cohorts, allowing extracted patters to be used in a clinical context. The modular design of KielMAT allows the toolbox to be easily extended to incorporate relevant algorithms which will be developed in the research community. The toolbox is designed to be user-friendly and is accompanied by a comprehensive documentation and practical examples, while the underlying data structures build on the Motion BIDS specification (Jeung et al., 2024). The KielMAT toolbox is intended to be used by researchers and clinicians to analyze human motion data from various recording modalities and to promote the utilization of open-source software in the field of human motion analysis.

Statement of need

Physical mobility is an essential aspect of health, as impairment in mobility is associated with reduced quality of life, falls, hospitalization, mortality, and other adverse events in many chronic conditions. Traditional mobility measures include patient-reported outcomes, objective clinical assessments, and subjective clinical assessments. These measures are linked to the perception and capacity aspects of health, which often fail to show relevant effects on daily function at an individual level (Maetzler et al., 2021). Perception involves surveys and patient-reported outcomes that capture how individuals feel about their own functional abilities, while capacity refers to clinical assessments of an individual's ability to perform various tasks. To complement both patient-reported (perception) and clinical (capacity) assessment approaches, digital health technology (DHT) introduces a new paradigm for assessing daily function. By using

[*] co-first author
[†] co-first author

wearable devices, DHT provides objective insights into an individual's functional performance, directly linking it to the International Classification of Functioning, Disability and Health (ICF) framework (Üstun et al., 2003; World Health Organization, 2001) for assessing how people perform in everyday life activities. (Buckley et al., 2019; Celik et al., 2021; Fasano & Mancini, 2020; Hansen et al., 2018; Maetzler et al., 2021; Warmerdam et al., 2020). DHT allows an objective impression of how patients function in everyday life and their ability to routinely perform everyday activities (Buckley et al., 2019; Celik et al., 2021; Hansen et al., 2018). Nonetheless, due to several persisting challenges in this field, current tools and techniques are still in their infancy (Micó-Amigo et al., 2023a). Many studies often used proprietary software to clinically relevant features of mobility. The development of easy-to-use and open-source software is imperative for transparent features extraction in research and clinical settings. KielMAT addresses this gap by providing software for human mobility analysis, to be used by motion researchers and clinicians, while promoting open-source practices. The conceptual framework builds on Findable, Accessible, Interoperable and Reusable (FAIR) data principles to encourage the use of open source software as well as facilitate data sharing and reproducibility in the field of human motion analysis (Wilkinson et al., 2016). The KielMAT comprises several modules which are implemented and validated with different dataset and each serving distinct purposes in human motion analysis:

1. Gait Sequence Detection (GSD): Identifies walking bouts to analyze gait patterns and abnormalities, crucial for neurological and biomechanical assessments.
2. Initial Contact Detection (ICD): Pinpoints the moment of initial foot contact during walking, aiding in understanding gait dynamics and stability.
3. Physical Activity Monitoring (PAM): Determines the intensity level of physical activities based on accelerometer signals.

These modules are pivotal because they enable researchers and clinicians to extract meaningful insights from motion data captured in various environments and conditions. These modules are designed to process data from wearable devices, which offer distinct advantages over vision-based approaches. wearable devices such as IMUs provide continuous monitoring capabilities, enabling users to wear them throughout the day in diverse settings without logistical constraints posed by camera-based systems.

State of the field

With the growing availability of digital health data, open-source implementations of relevant algorithms are increasingly becoming available. From the Mobilise-D consortium, the recommended algorithms for assessing real-world gait were released, but these algorithms were developed in MATLAB, that is not free to use (Micó-Amigo et al., 2023b; *Mobilise-D Consortium*, 2019). Likewise, an algorithm for the estimation of gait quality was released, but it is also only available in MATLAB (Schooten, 2016; The MathWorks Inc., 2022). Alternatively, open-source, Python packages are available, for example to detect gait and extract gait features from a low back-worn inertial measurement unit (IMU) (Czech & Patel, 2019), or from two feet-worn IMUs (Küderle et al., 2024). These advancements facilitate broader accessibility and usability across research and clinical applications. Additionally, innovative approaches like Mobile GaitLab focus on video input for predicting key gait parameters such as walking speed, cadence, knee flexion angle at maximum extension, and the Gait Deviation Index, leveraging open-source principles and designed to be accessible to non-computer science specialists (Kidziński et al., 2020a, 2020b). Moreover, tools such as Sit2Stand and Sports2D contribute to this landscape by offering user-friendly platforms for assessing physical function through automated analysis of movements like sit-to-stand transitions and joint angles from smartphone videos (Sports2D) (Boswell et al., 2023; Pagnon, 2023). KielMAT builds forth on these toolboxes by providing a module software package that goes beyond the analysis of merely gait, and extends these analyses by additionally allowing for the physical activity monitoring (Van Hees et al., 2013) and other daily life-relevant movements, such as sit-to-stand and stand-to-sit transitions (Pham et al., 2017) as well as turns (Pham et al., 2018).

Provided Functionality

KielMAT offers a comprehensive suite of algorithms for motion data processing in neuroscience and biomechanics. Currently, the toolbox includes implementations for gait sequence detection (GSD) and initial contact detection (ICD), whereas algorithms for postural transition analysis (Pham et al., 2017) and turns (Pham et al., 2018) are under current development. KielMAT is built on principles from the Brain Imaging Data Structure (BIDS) (Gorgolewski et al., 2016) and for the motion analysis data are organized similar to the Motion-BIDS specifications (Jeung et al., 2024).

Dataclass

Supporting the data curation as specified in BIDS, data are organized in recordings, where recordings can be simultaneously collected with different tracking systems (e.g., an camera-based optical motion capture system and a set of IMUs). A tracking system is defined as a group of motion channels that share hardware properties (the recording device) and software properties (the recording duration and number of samples). Loading of a recording returns a `KielMATRecording` object, that holds both `data` and `channels`. Here, `data` are the actual time series data, where `channels` provide information (meta-data) on the time series type, component, the sampling frequency, and the units in which the time series (channel) are recorded.

Modules

The data can be passed to algorithms that are organized in different modules, such as GSD and ICD. For example, the accelerometer data from a lower back-worn IMU can be passed to the gait sequence detection algorithm (Paraschiv-Ionescu et al., 2020, 2019). Next, the data can be passed to the initial contact detection algorithm (Paraschiv-Ionescu et al., 2019) to returns the timings of initial contacts within each gait sequence (Figure 1).

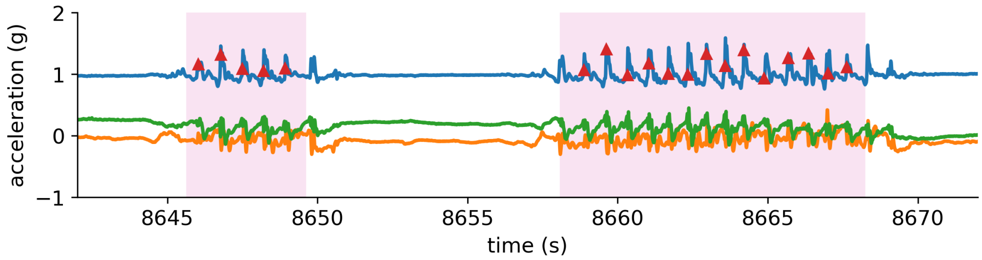

Figure 1: A representative snippet of acceleration data from a low back-worn with the detected gait sequences (pink-shaded background) and the detected initial contacts (red triangles).

Installation and usage

The KielMAT package is implemented in Python (>=3.10) and is freely available under a Non-Profit Open Software License version 3.0. The stable version of the package can be installed from PyPI.org using `pip install kielmat`. Users and developers can also install the toolbox from source from GitHub. The documentation of the toolbox provides detailed instructions on installation, conceptual framework and tutorial notebooks for basic usage and specific algorithms. Data used in the examples have been collected in accordance with the Declaration of Helsinki.

How to contribute

KielMAT is a community effort, and any contribution is welcomed. The project is hosted on https://github.com/neurogeriatricskiel/KielMAT. In case you want to add new algorithms, it is suggested to fork the project and, after finalizing the changes, to create a pull request from a fork.

Acknowledgements

The authors would like to thank every person who provided data which has been used in the development and validation of the algorithms in the KielMAT toolbox. The authors declare no competing interests.

References

Boswell, M. A., Kidziński, Ł., Hicks, J. L., Uhlrich, S. D., Falisse, A., & Delp, S. L. (2023). Smartphone videos of the sit-to-stand test predict osteoarthritis and health outcomes in a nationwide study. *Npj Digital Medicine*, *6*(1), 32. https://doi.org/10.1038/s41746-023-00775-1

Buckley, C., Alcock, L., McArdle, R., Rehman, R. Z. U., Del Din, S., Mazzà, C., Yarnall, A. J., & Rochester, L. (2019). The Role of Movement Analysis in Diagnosing and Monitoring Neurodegenerative Conditions: Insights from Gait and Postural Control. *Brain Sciences*, *9*(2), 34. https://doi.org/10.3390/brainsci9020034

Celik, Y., Stuart, S., Woo, W. L., & Godfrey, A. (2021). Gait analysis in neurological populations: Progression in the use of wearables. *Medical Engineering & Physics*, *87*, 9–29. https://doi.org/10.1016/j.medengphy.2020.11.005

Czech, M. D., & Patel, S. (2019). GaitPy: An open-source python package for gait analysis using an accelerometer on the lower back. *Journal of Open Source Software*, *4*(43), 1778. https://doi.org/10.21105/joss.01778

Fasano, A., & Mancini, M. (2020). Wearable-based mobility monitoring: The long road ahead. *The Lancet Neurology*, *19*(5), 378–379. https://doi.org/10.1016/S1474-4422(20)30033-8

Gorgolewski, K. J., Auer, T., Calhoun, V. D., Craddock, R. C., Das, S., Duff, E. P., Flandin, G., Ghosh, S. S., Glatard, T., Halchenko, Y. O., Handwerker, D. A., Hanke, M., Keator, D., Li, X., Michael, Z., Maumet, C., Nichols, B. N., Nichols, T. E., Pellman, J., … Poldrack, R. A. (2016). The brain imaging data structure, a format for organizing and describing outputs of neuroimaging experiments. *Scientific Data*, *3*(1), 160044. https://doi.org/10.1038/sdata.2016.44

Hansen, C., Sanchez-Ferro, A., & Maetzler, W. (2018). How Mobile Health Technology and Electronic Health Records Will Change Care of Patients with Parkinson's Disease. *Journal of Parkinson's Disease*, *8*(s1), S41–S45. https://doi.org/10.3233/JPD-181498

Jeung, S., Cockx, H., Appelhoff, S., Berg, T., Gramann, K., Grothkopp, S., Warmerdam, E., Hansen, C., Oostenveld, R., & Welzel, J. (2024). Motion-BIDS: An extension to the brain imaging data structure to organize motion data for reproducible research. *Scientific Data*, *11*(1), 716. https://doi.org/10.1038/s41597-024-03559-8

Kidziński, Ł., Yang, B., Hicks, J. L., Rajagopal, A., Delp, S. L., & Schwartz, M. H. (2020a). Deep neural networks enable quantitative movement analysis using single-camera videos.

Nature Communications, *11*(1), 4054. https://doi.org/10.1038/s41467-020-17807-z

Kidziński, Ł., Yang, B., Hicks, J. L., Rajagopal, A., Delp, S. L., & Schwartz, M. H. (2020b). Mobile-gaitlab. In *GitHub repository*. GitHub. https://github.com/stanfordnmbl/mobile-gaitlab

Küderle, A., Ullrich, M., Roth, N., Ollenschläger, M., Ibrahim, A. A., Moradi, H., Richer, R., Seifer, A.-K., Zürl, M., Sîmpetru, R. C., Herzer, L., Prossel, D., Kluge, F., & Eskofier, B. M. (2024). Gaitmap—an open ecosystem for IMU-based human gait analysis and algorithm benchmarking. *IEEE Open Journal of Engineering in Medicine and Biology*, *5*, 163–172. https://doi.org/10.1109/OJEMB.2024.3356791

Maetzler, W., Rochester, L., Bhidayasiri, R., Espay, A. J., Sánchez-Ferro, A., & Uem, J. M. T. van. (2021). Modernizing Daily Function Assessment in Parkinson's Disease Using Capacity, Perception, and Performance Measures. *Movement Disorders*, *36*(1), 76–82. https://doi.org/10.1002/mds.28377

Micó-Amigo, M. E., Bonci, T., Paraschiv-Ionescu, A., Ullrich, M., Kirk, C., Soltani, A., Küderle, A., Gazit, E., Salis, F., Alcock, L., Aminian, K., Becker, C., Bertuletti, S., Brown, P., Buckley, E., Cantu, A., Carsin, A.-E., Caruso, M., Caulfield, B., … for the Mobilise-D consortium. (2023a). Assessing real-world gait with digital technology? Validation, insights and recommendations from the Mobilise-D consortium. *Journal of NeuroEngineering and Rehabilitation*, *20*(1), 78. https://doi.org/10.1186/s12984-023-01198-5

Micó-Amigo, M. E., Bonci, T., Paraschiv-Ionescu, A., Ullrich, M., Kirk, C., Soltani, A., Küderle, A., Gazit, E., Salis, F., Alcock, L., Aminian, K., Becker, C., Bertuletti, S., Brown, P., Buckley, E., Cantu, A., Carsin, A.-E., Caruso, M., Caulfield, B., … for the Mobilise-D consortium. (2023b). Mobilise-d technical validation study recommended algorithms. In *GitHub repository*. GitHub. https://github.com/mobilise-d/Mobilise-D-TVS-Recommended-Algorithms

Mobilise-D consortium. (2019). https://mobilise-d.eu/

Pagnon, D. (2023). Sports2D - angles from video. In *GitHub repository*. GitHub. https://doi.org/10.5281/zenodo.7903963

Paraschiv-Ionescu, A., Newman, C. J., Carcreff, L., Gerber, C. N., Armand, S., & Aminian, K. (2019). Locomotion and cadence detection using a single trunk-fixed accelerometer: Validity for children with cerebral palsy in daily life-like conditions. *Journal of Neuroengineering and Rehabilitation*, *16*(1), 1–11. https://doi.org/10.1186/s12984-019-0494-z

Paraschiv-Ionescu, A., Soltani, A., & Aminian, K. (2020). Real-world speed estimation using single trunk IMU: Methodological challenges for impaired gait patterns. *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*, 4596–4599. https://doi.org/10.1109/EMBC44109.2020.9176281

Pham, M. H., Elshehabi, M., Haertner, L., Heger, T., Hobert, M. A., Faber, G. S., Salkovic, D., Ferreira, J. J., Berg, D., Sanchez-Ferro, Á., Dieën, J. H. van, & Maetzler, W. (2017). Algorithm for Turning Detection and Analysis Validated under Home-Like Conditions in Patients with Parkinson's Disease and Older Adults using a 6 Degree-of-Freedom Inertial Measurement Unit at the Lower Back. *Frontiers in Neurology*, *8*, 135. https://doi.org/10.3389/fneur.2017.00135

Pham, M. H., Warmerdam, E., Elshehabi, M., Schlenstedt, C., Bergeest, L.-M., Heller, M., Haertner, L., Ferreira, J. J., Berg, D., Schmidt, G., Hansen, C., & Maetzler, W. (2018). Validation of a Lower Back "Wearable"-Based Sit-to-Stand and Stand-to-Sit Algorithm for Patients With Parkinson's Disease and Older Adults in a Home-Like Environment. *Frontiers in Neurology*, *9*, 652. https://doi.org/10.3389/fneur.2018.00652

Schooten, M. A. R. van, Kimberley S. AND Pijnappels. (2016). Estimate gait quality composite. In *GitHub repository*. GitHub. https://github.com/KimvanS/EstimateGaitQualityComposite

The MathWorks Inc. (2022). *MATLAB version: 9.13.0 (R2022b)*. The MathWorks Inc. https://www.mathworks.com

Üstun, T. B., Chatterji, S., Bickenbach, J., Kostanjsek, N., & Schneider, M. (2003). The international classification of functioning, disability and health: A new tool for understanding disability and health. *Disability and Rehabilitation*, *25*(11-12), 565–571. https://doi.org/10.1080/0963828031000137063

Van Hees, V. T., Gorzelniak, L., Dean León, E. C., Eder, M., Pias, M., Taherian, S., Ekelund, U., Renström, F., Franks, P. W., Horsch, A., & others. (2013). Separating movement and gravity components in an acceleration signal and implications for the assessment of human daily physical activity. *PloS One*, *8*(4), e61691. https://doi.org/10.1371/journal.pone.0061691

Warmerdam, E., Hausdorff, J. M., Atrsaei, A., Zhou, Y., Mirelman, A., Aminian, K., Espay, A. J., Hansen, C., Evers, L. J. W., Keller, A., Lamoth, C., Pilotto, A., Rochester, L., Schmidt, G., Bloem, B. R., & Maetzler, W. (2020). Long-term unsupervised mobility assessment in movement disorders. *The Lancet Neurology*, *19*(5), 462–470. https://doi.org/10.1016/S1474-4422(19)30397-7

Wilkinson, M. D., Dumontier, M., Aalbersberg, Ij. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., Silva Santos, L. B. da, Bourne, P. E., & others. (2016). The FAIR guiding principles for scientific data management and stewardship. *Scientific Data*, *3*(1), 1–9. https://doi.org/10.1038/sdata.2016.18

World Health Organization (Ed.). (2001). *International classification of functioning, disability and health: ICF*. World Health Organization. ISBN: 978-92-4-154542-6