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Towards a Model-based Digital Twin for Gait Analysis in Parkinson-Related Assessment

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Abstract: Step-width variation and foot-placement are relevant measures for Parkinson-related gait assessment, but are difficult to derive robustly from compact wearable sensor setups. Previous work within the same project used body-worn magnetoelectric sensors to estimate step width from relative distance measurements, but did not provide a continuous kinematic body representation. This work presents a work-in-progress transition toward a model-based, digital-twin-oriented framework for inertial measurement unit (IMU)-based gait analysis. The framework combines a modular processing chain, a hierarchical kinematic skeleton model, and a planned state-space estimation approach for recursive pose reconstruction from accelerometer and gyroscope signals. The current implementation comprises the individualized kinematic model, recording-specific marker alignment, and its integration into a shared simulation and processing framework. The kinematic model is individualized through patient-specific segment lengths and recording-specific marker offsets, while dynamic updating through wearable IMU signals is planned as a subsequent step. The ensuing development steps also include recursive state-space estimation and validated derivation of gait parameters.

Keywords: digital twin, gait analysis, Parkinson-related assessment, state-space estimation, wearable sensors, movement analysis

1 Introduction

Spatiotemporal gait parameters are relevant for clinical movement analysis, including Parkinson-related assessment [1]. In particular, step-width variation and foot-placement-related measures are of interest because they reflect mediolateral gait control and stability and are associated with gait instability [2, 3]. However, these quantities are difficult to obtain robustly from compact wearable sensor setups when only local segment signals or direct pairwise distance measurements are available.

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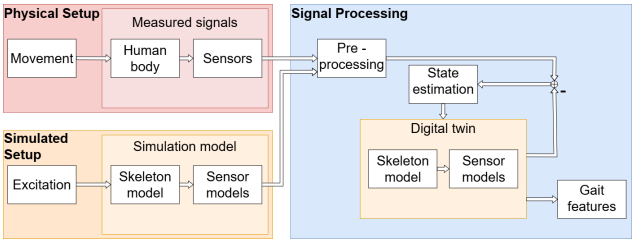


Fig. 1: Overview of the proposed framework. Measured and simulated sensor signals are processed within a shared model-based pipeline comprising preprocessing, state estimation, and a digital twin. The framework is intended to support the derivation of clinically relevant gait measures such as step-width variation and foot placement.

Within the same project line, Hoffmann et al. used body-worn magnetoelectric (ME) sensors to estimate step-width-related quantities during treadmill walking [1]. That study demonstrated the potential of wearable spatial sensing, but the measured quantity remained a proxy and showed systematic differences relative to anatomically defined heel-based gait descriptors [1]. The main limitation was therefore not the sensing principle itself, but the lack of an explicit biomechanical model from which clinically meaningful gait descriptors can be derived in a flexible and interpretable manner.

The present work addresses this limitation by introducing a model-based digital twin for gait analysis as an extension of the previous ME-based approach. The framework combines a hierarchical kinematic skeleton model, shared simulation and online processing, and a planned recursive state-space estimation concept to provide a common model-based representation for wearable sensor based gait analysis. This paper focuses on the concept, architecture, and current software status of the resulting work-in-progress system system, as a basis for clinical validation in the next step. Figure 1 provides an overview of the proposed framework.

2 Framework Concept

The proposed framework is organized as a modular processing chain consisting of a kinematic-model module, a sensor and measurement layer, and a planned state-space estimation stage. The kinematic model forms the core of the digital-twin-oriented framework and manages the skeleton definition, hier-

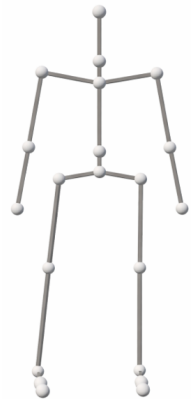


Fig. 2: Hierarchical kinematic model of the proposed framework.

archical parent-child relations, model activation, and sensor-to-segment assignment. The same skeleton structure is used in simulation and in the real-time processing path. This shared representation is intended to ensure consistent model assumptions across development stages and to provide a common basis for comparing different sensing concepts. The hierarchical kinematic skeleton transforms local joint states into global segment positions and orientations by forward kinematics and currently supports parent-child relations, patient-specific segment adaptation, recording-specific marker offsets, and configurable sensor assignments. As illustrated in Figure 2, the model layer links wearable measurements to a biomechanical representation of gait while remaining independent of a specific sensor modality. This model layer is the main methodological extension beyond direct distance-based approaches. It provides an intermediate kinematic representation that preserves anatomical dependencies and supports consistent interpretation of wearable measurements. The modular structure separates biomechanical representation, sensor assignment, and signal interpretation. Changes in sensor number or placement primarily affect the observation side, while the anatomical model remains unchanged. The intended wearable input consists of IMU-based accelerometer (ACC) and gyroscope (GYR) signals. The corresponding ACC/GYR signal simulation, measurement models, and recursive state-space-based pose reconstruction are currently under development. Table 1 summarizes the current implementation status.

Tab. 1: Implementation status of framework components.

Component	Status
Kinematic skeleton model	**Implemented**
Patient-specific segment lengths	**Implemented**
Sensor objects and assignments	**Implemented**
ACC/GYR signal simulation	**Under development**
State-space pose reconstruction	**Conceptual/planned**
Gait-parameter derivation/validation	**Planned**

3 State-space Estimation Concept

The planned estimation strategy is based on a state-space model in which body pose is estimated recursively from wearable sensor signals. The state vector is defined as

$$\boldsymbol{x}(n) = \begin{bmatrix} \boldsymbol{\theta}(n) \\ \dot{\boldsymbol{\theta}}(n) \\ \boldsymbol{b}(n) \end{bmatrix},$$

where $\boldsymbol{\theta}_k$ contains the joint angles, $\dot{\boldsymbol{\theta}}_k$ the corresponding angular velocities, and $\boldsymbol{b}_k$ slow bias or drift states. This state is intended to provide a biomechanically interpretable latent description of gait rather than a direct mapping from raw sensor signals to isolated output parameters.

The process model follows a constant-velocity assumption:

$$\boldsymbol{\theta}(n+1) = \boldsymbol{\theta}(n) + \Delta t\, \dot{\boldsymbol{\theta}}(n),$$

$$\dot{\boldsymbol{\theta}}(n+1) = \dot{\boldsymbol{\theta}}(n) + \boldsymbol{w}_{\dot{\theta}}(n),$$

$$\boldsymbol{b}(n+1) = \boldsymbol{b}(n) + \boldsymbol{w}_b(n).$$

In compact form, this yields

$$\boldsymbol{x}(n+1) = \boldsymbol{A}\boldsymbol{x}(n) + \boldsymbol{w}(n)$$

with

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{I} & \Delta t\, \boldsymbol{I} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{I} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{I} \end{bmatrix}, \qquad \boldsymbol{w}(n) \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{Q}),$$

where $\boldsymbol{A}$ denotes the discrete state transition matrix and $\boldsymbol{Q}$ the process noise covariance.

The measurement model is written as

$$\boldsymbol{z}(n) = \boldsymbol{h}\Big(\boldsymbol{\theta}(n), \dot{\boldsymbol{\theta}}(n), \boldsymbol{b}(n)\Big) + \boldsymbol{v}(n),$$

with

$$\boldsymbol{v}(n) \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{R}),$$

where $\boldsymbol{z}_k$ denotes the measurement vector, $\boldsymbol{h}(\cdot)$ the nonlinear measurement function, and $\boldsymbol{R}$ the measurement noise covariance. In the proposed framework, the digital twin provides the forward mapping from latent joint states to segment poses and expected sensor signals:

$$\boldsymbol{h}(\boldsymbol{x}(n)) = h_{\mathrm{sens}}\Big(f_{\mathrm{kin}}\big(\boldsymbol{\theta}(n)\big), \dot{\boldsymbol{\theta}}(n), \boldsymbol{b}(n)\Big),$$

where $f_{\mathrm{kin}}(\cdot)$ denotes the forward kinematics and $h_{\mathrm{sens}}(\cdot)$ the sensor model.

Because the measurement model is nonlinear, the estimator is formulated as an extended Kalman filter [4]. The corresponding Jacobian is

$$\boldsymbol{H}(n) = \frac{\partial \boldsymbol{h}}{\partial \boldsymbol{x}}\Big|_{\boldsymbol{x}=\hat{\boldsymbol{x}}(n|n-1)}.$$

The prediction step is given by

$$\hat{\boldsymbol{x}}(n|n-1) = \boldsymbol{A}\hat{\boldsymbol{x}}(n-1|n-1),$$

$$\widehat{\boldsymbol{P}}(n|n-1) = \boldsymbol{A}\widehat{\boldsymbol{P}}(n-1|n-1)\boldsymbol{A}^T + \boldsymbol{Q},$$

where $\hat{\boldsymbol{x}}_{k|k-1}$ denotes the predicted state estimate and $\widehat{\boldsymbol{P}}_{k|k-1}$ the corresponding predicted covariance. The innovation is computed as

$$\hat{\boldsymbol{y}}(n) = \boldsymbol{z}(n) - \boldsymbol{h}\big(\hat{\boldsymbol{x}}(n|n-1)\big),$$

and the Kalman gain becomes

$$\boldsymbol{K}(n) = \widehat{\boldsymbol{P}}(n|n-1)\boldsymbol{H}(n)^T\Big(\boldsymbol{H}(n)\widehat{\boldsymbol{P}}(n|n-1)\boldsymbol{H}(n)^T + \boldsymbol{R}\Big)^{-1}.$$

The state update is then written as

$$\hat{\boldsymbol{x}}(n|n) = \hat{\boldsymbol{x}}(n|n-1) + \boldsymbol{K}(n)\Big(\boldsymbol{z}(n) - \boldsymbol{h}\big(\hat{\boldsymbol{x}}(n|n-1)\big)\Big),$$

and the covariance update becomes

$$\widehat{\boldsymbol{P}}(n|n) = \big(\boldsymbol{I} - \boldsymbol{K}(n)\boldsymbol{H}(n)\big)\widehat{\boldsymbol{P}}(n|n-1).$$

Within the proposed framework, this recursive estimation scheme combines temporal state propagation with model-based interpretation of sensor observations. At the current stage, the estimation concept should be understood as a planned methodological component rather than a fully implemented and validated module. The observation model is explicitly tied to the digital twin rather than defined as a purely data-driven regression step. The measurement function is therefore intended to express how a hypothesized body configuration would appear under a given wearable sensor setup. This creates a direct link between latent joint states and measurable sensor signals and makes the estimation problem structurally adaptable to different sensing modalities. Beyond pose reconstruction, the latent state representation can provide a structured basis for deriving gait parameters above the raw sensor level. Once segment poses and relative foot positions are available within a consistent body-centered coordinate system, quantities such as step width, stride-dependent foot placement, or temporal inter-limb relations can in principle be computed from the reconstructed motion sequence. Combined with suitable pattern-recognition approaches, this representation may further support detection of characteristic gait events such as foot contact timing or transitions between gait phases. The targeted parameters are therefore not introduced as separate estimation outputs, but as variables derived from a shared biomechanical representation.

3.1 Planned Evaluation

The planned evaluation will focus on validating the spatial reconstruction provided by the digital-twin-oriented framework against an external optical motion capture (OMC) reference. The primary objective is to assess whether the framework can reconstruct body configuration in a geometrically consistent manner from wearable IMU signals. At this stage, the evaluation is intended as a methodological validation of the estimated pose and sensor-associated spatial positions rather than as a clinical validation of derived gait measures. Wearable IMU measurements and OMC data are intended to be recorded for the same gait sequences. The IMU pathway will provide accelerometer and gyroscope signals as input to the planned measurement models and recursive state-space estimation pipeline. No separate biomechanical parallel model based on OMC is planned; instead, OMC is used solely to compare the reconstructed positions obtained from the digital-twin-oriented estimation pathway with an independent reference. The comparison will primarily focus on the estimated positions of the wearable sensors as represented within the kinematic model. This allows the evaluation to determine how closely the reconstructed sensor locations match the spatial reference provided by OMC. Segment positions and joint-related points may serve as additional reference quantities where appropriate, but the main objective is to assess whether the proposed model-based estimation approach can reconstruct sensor-associated spatial positions reliably from wearable IMU data. This validation strategy is considered a necessary intermediate step before extending the analysis toward derived gait parameters such as step-width variation or foot placement. Once the geometric plausibility of the reconstructed pose has been established, the same model-based representation can serve as the basis for future evaluation of clinically relevant gait descriptors. Depending on the clinical target parameter and reference measure, future studies may additionally consider non-inferiority analyses to compare wearable-sensor-based estimates with established laboratory-based gait assessment.

4 Simulation and Intended Clinical Use

Simulation is a second key component of the intended framework. In its planned form, predefined body motion from the kinematic model will be used to generate virtual IMU signals, allowing accelerometer and gyroscope measurements to be simulated under controlled conditions. This simulation layer is intended to support algorithm development, controlled testing,

and the comparison of sensor configurations within a shared model environment. In particular, it will enable systematic investigation of how sensor number and placement influence measurement outcomes and the later derivation of gait parameters. By allowing virtual sensors to be assigned to alternative body locations, the framework provides a basis for evaluating design choices before transferring them to wearable measurements. From an application perspective, the framework is intended, as a first step, for gait analysis in Parkinson-related assessment, with a focus on target parameters such as step-width variation and foot placement. Step-width variation provides a direct link to the earlier project line [1], while foot placement exemplifies a quantity that benefits from a continuous kinematic representation rather than a direct sensor-level measure. In this way, the framework is intended as a wearable complement to laboratory-based gait analysis and as a basis for future estimation of biomechanical gait parameters from IMU data.

5 Current Status and Outlook

The current implementation comprises the modular software architecture, the hierarchical kinematic model with parent-child segment relations, configurable sensor assignment, and the integration of the pose-estimation and state-space concepts into the existing processing chain. The pipeline up to the kinematic-model module is functional and has been verified at the software level, including model initialization, structural integration, and interface-level consistency within the framework. In addition, the kinematic model can already be driven by recorded motion data, enabling replay of gait sequences from existing motion-capture datasets within the digital twin environment.

Several key components, however, remain under development. These include the final definition of the state vector, the detailed process and measurement models, the Kalman-based recursive estimator, the integration of real IMU (inertial measurement unit) data, and the derivation of gait parameters within the estimation pathway. The simulation environment is likewise not yet complete, particularly with regard to inertial sensor simulation. Accordingly, the present system should be regarded as a methodological framework in progress rather than a finalized analysis tool. No human measurements and no quantitative validation are reported at this stage. The planned validation will use optical motion capture as an external spatial reference for assessing reconstructed sensor positions, segment positions, and derived gait parameters once the IMU simulation and recursive estimation pipeline are available.

The main contribution of the present work therefore lies in defining the transition from a sensor-specific proxy-based approach toward a more general model-based framework for wearable gait analysis. Building on earlier work [1], the proposed system establishes a flexible basis for future development, extension to additional sensing modalities, and subsequent validation of model-based gait reconstruction and parameter derivation.

6 Conclusion

This paper presents a work-in-progress framework for a model-based digital twin for gait analysis in physiological and pathological states. The approach combines a hierarchical kinematic model, a planned state-space estimation concept, and a shared model basis for simulation and online processing. The current implementation establishes the architectural foundation for model-based interpretation of wearable sensor data. After understanding the performance across sensor configurations, this archtiecture could be potentially used for the derivation of clinically relevant gait parameters. Completion of the recursive estimation framework and validation against optical motion capture remain the next steps in the further development of the system.

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