Quantifying Joint Stiffness During Movement: A Quantitative Comparison of Time-Varying System Identification Methods

Mark van de Ruit, Winfred Mugge, and Alfred C. Schouten

Abstract Careful control of joint impedance, or dynamic joint stiffness, is crucial for successful performance of movement. Time-varying system identification (TV-SysID) enables quantification of joint impedance during movement. Several TV-SysID methods exist, but have never been systematically compared. Here, we simulate time-varying joint behavior and propose three performance metrics that enable to quantify and compare TV-SysID methods. Time-varying joint stiffness is simulated using a square wave and subsequently estimated with three TV-SysID methods: the ensemble, short data segment, and basis impulse response function method. These methods were compared based on (1) bias with respect to the simulated joint stiffness, (2) random error across 100 simulation trials, and (3) maximum adaptation speed in joint stiffness that can be captured. This approach revealed that each TV-SysID method has its own unique properties. The simulation method and performance metrics pave the way for developing a framework to quantify the strengths and weaknesses of TV-SysID algorithms for estimating joint impedance.

1 Introduction

Joint impedance is a dynamical property of our neuromuscular system that describes the relationship between joint displacement and restoring torque. Joint impedance

This work is part of the talent programme VENI with project number 17351, which is financed by the Dutch Research Council (NWO).

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D. Torricelli et al. (eds.), *Converging Clinical and Engineering Research on Neurorehabilitation IV*, Biosystems & Biorobotics 28,
https://doi.org/10.1007/978-3-030-70316-5_82

is determined by the inertial, viscous, and elastic properties of a joint [1]. Improper control of joint impedance during movement has been associated with movement disorders such as seen after stroke or in people with Parkinson's Disease [2, 3]. Knowledge on joint impedance is not only important for better understanding of impairments of motor control, but is also crucial for providing intuitive exoskeletons, development of active biomimetic prosthetics and design of haptic robots that ecologically interact with humans. The challenge is to accurately identify joint impedance during movement.

Human joint impedance, specifically joint damping and joint stiffness, have been demonstrated to change with joint torque, joint angle, and muscle activation level, thereby varying tremendously throughout a movement [4, 5]. Time-varying system identification (TV-SysID) enables the identification of changing joint properties over time. Thirty years of research have seen development of various TV-SysID methods that are specifically suited for application to data recorded from human joints [e.g. 6–8]. TV-SysID algorithms hugely differ with respect to a priori assumptions, amount of data required and speed of time-varying behavior that can be captured. Yet, we lack means to systematically compare performance of TV-SysID methods and quantify their key properties. Here, we use a simulation of time-varying joint behavior and three quantification metrics to construct a framework for systematic comparison of TV-SysID methods for the identification of joint impedance.

2 Methods

2.1 Simulation Study

Time-varying joint stiffness was simulated using a model of human joint dynamics. A simple time-varying 2nd-order mass-spring-damper model $H_{joint}(s)$ can describe the dynamics of a joint when only small rotations are applied:

$$H_{joint}(s, t) = I(t)s^2 + b(t)s + k(t) \tag{1}$$

in which s is the Laplace variable and equals $j2\pi f$ (f represents the frequency). $H_{joint}(s, t)$ represents the intrinsic joint dynamics where I is the limb inertia, b the joint viscosity and k the joint stiffness.

An anti-causal open-loop model was implemented in MATLAB 2019b—Simulink 9.7 (The MathWorks, Inc., Natick, Massachusetts, United States) as:

$$y(t) = H_{joint}(s, t)u(t) + v(t) \tag{2}$$

where $u(t)$ is the angular input perturbation signal, $y(t)$ the measured output torque and $v(t)$ is the measurement noise (Fig. 1). Measurement noise $v(t)$ was added as

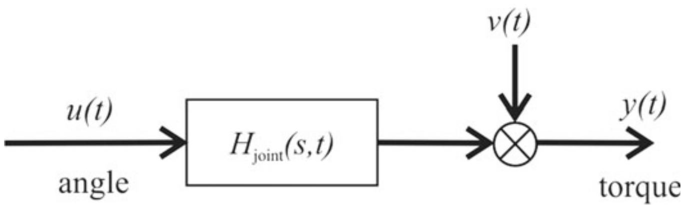

Fig. 1 The simulation model used with $H_{joint}(s,t)$ representing the time-varying joint dynamics, $u(t)$ the angular perturbation input signal, $y(t)$ the measured output torque and $v(t)$ the measurement noise

a 40 Hz low-pass filtered (4th-order Butterworth) normally distributed noise and scaled such to achieve a signal-to-noise ratio (SNR) of 10 dB.

The limb inertia (I) and joint viscosity (b) in the model were taken as 0.02 kgm^2 and 2.2 Nms/rad respectively, to represent the human ankle joint, and considered time-invariant. Joint stiffness (k) was considered time-varying, following a 0.5 Hz square wave, transitioning between 50 and 150 Nm/rad.

The model's perturbation input $u(t)$ was a 5 Hz low-pass filtered (2nd-order Butterworth) noise signal.

Each simulation trial lasted 150 s and was repeated 100 times with a new random input and noise realization ($f_s = 1000$ Hz).

2.2 Data Analysis

The data from the simulations were analyzed using three TV-SysID methods:

- Ensemble Impulse Response Function (eIRF) [6]: Assumes time-invariant system dynamics at each time point across the realizations, i.e., the ensemble. Therefore, uses time-invariant system identification at each time point to construct a time-varying impulse response function (TV-IRF).
- Short Data Segments (SDS) [8]: Extension of eIRF in which local time-invariant dynamics is not only assumed across realizations but also across a short time window, resulting in the need for less data.
- Basis impulse response function (bIRF) [7]: Extension of eIRF where the TV-IRFs are approximated by a linear combination of cubic B-splines basis functions. This method assumes system parameters to vary smoothly with time.

Three metrics were used to assess the quality of the estimate of time-varying joint stiffness. First, the bias error describes the estimation error with respect to the simulated simulation joint stiffness:

$$e_B = \sqrt{\frac{\Delta t}{T} \sum_{i=1}^{T/\Delta t} \left(\overline{\hat{K}}_i(i\Delta t) - K_i(i\Delta t) \right)^2}, \tag{3}$$

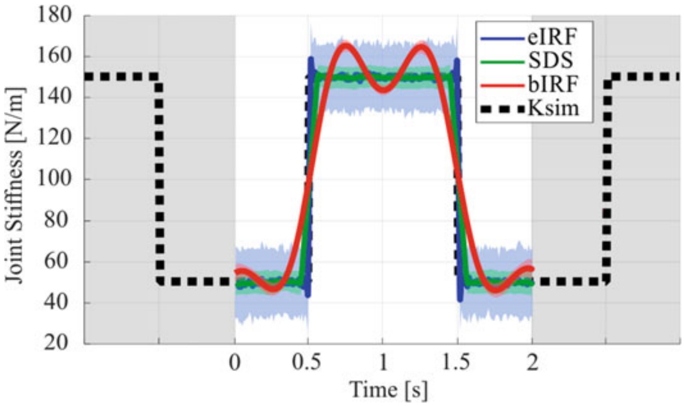

Fig. 2 Simulated and estimated joint stiffness. Data was segmented in 2 s periods and aligned before estimation by the eIRF, SDS and bIRF TV-SysID methods (mean ± 2 * S.D. of 100 trials—solid line and shaded area). The simulated time-varying joint stiffness (Ksim—dashed line) is added for reference

where $K(t)$ the simulated stiffness and $\overline{\hat{K}}(t)$ the mean estimated stiffness across all simulated trials. Second, the random error quantifies the variance of the estimate across simulation trials (noise sensitivity):

$$e_R = \sqrt{\frac{\Delta t}{S \Delta T} \sum_{i=1}^{T/\Delta t} \sum_{s=1}^{S} \left(\hat{K}_i(i\Delta t, s) - \overline{\hat{K}}_i(i\Delta t) \right)^2}, \tag{4}$$

where $\hat{K}(t, s)$ is the stiffness estimated at timepoint t for simulation trial s. Third, the slope, quantified by taking the maximum of the numerical derivative of estimated joint stiffness, provides a measure of the maximum speed in adaptation that can be captured.

3 Results

Figure 2 shows the estimated joint stiffness using all three TV-SysID methods. Bias error, random error and slope associated with these estimates of joint stiffness are summarized in Fig. 3. eIRF accurately captures simulated joint stiffness including the instantaneous change but does so with high variance. In contrast, SDS and bIRF provide an estimate with lower variance, but greater bias and flatter transition slopes.

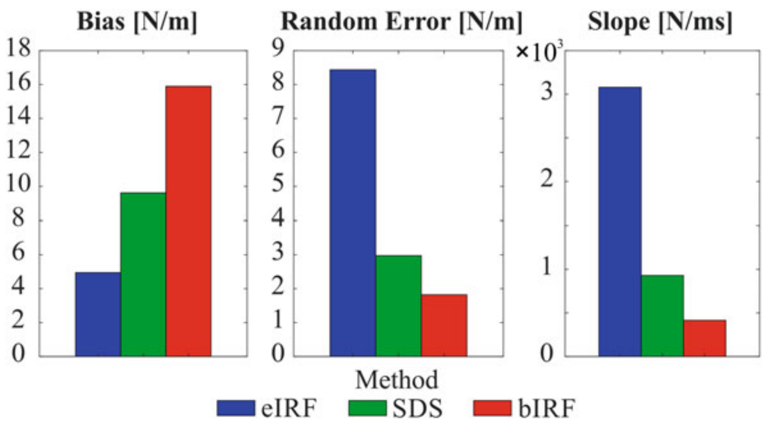

Fig. 3 Estimation performance for the eIRF, SDS and bIRF method

4 Conclusion

The results demonstrate the unique properties for each TV-SysID method. The presented simulation method and performance metrics enable researchers to systematically investigate the strengths and weaknesses of their newly developed algorithms or make a justified choice which TV-SysID method to use depending on their application. Further work will have to elucidate the effect of e.g. including time-varying joint damping, different noise types, different SNRs and different amounts of data, but also demonstrate the methods applicability on experimental data. Our work will be used to develop a framework for comparison of TV-SysID methods for the identification of human joint impedance.

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