Identification of Feedback Control in an Inverted Pendulum Model of Standing

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Introduction

Human standing is inherently unstable unless a controller is acting continuously. Identification of the feedback control system in human standing would provide information that can be incorporated in the design of control systems for powered exoskeleton and powered prosthetic limbs.
A direct approach for identification of the feedback control system is to observe the inputs (joint motion) and the outputs (joint torques) of the controller and determine a mathematical relationship between the two. It is, however, known that this approach can introduce bias when applied to observations on a closed loop system [1].

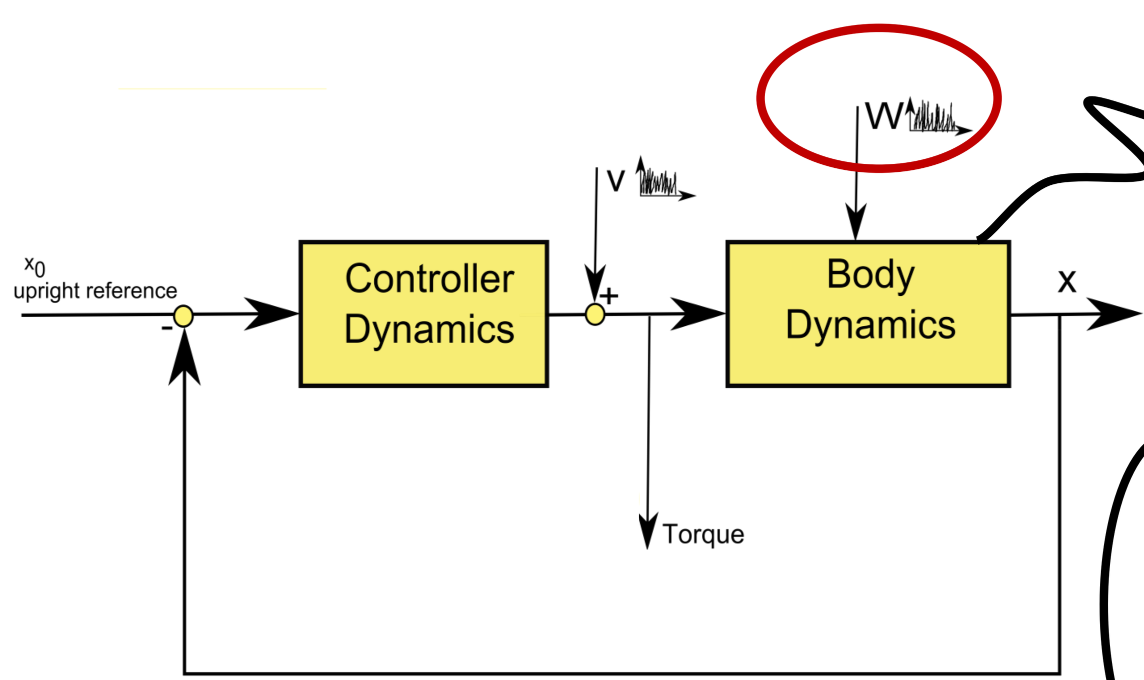
Fig. 1. Exoskeleton system

Research Question

To what extent can human feedback control during standing be estimated using the direct approach?

Test Data

Test data were generated by a realistic simulation of human standing. The plant is a double link inverted pendulum (DIP) with two joints representing the ankle and hip. The system is perturbed by controller noise (v) and by random horizontal accelerations of the surface (W).
The system was controlled by a proportional-derivative (PD) controller with a 2x4 matrix K of feedback gains, generating two torques T from the four state variables x.



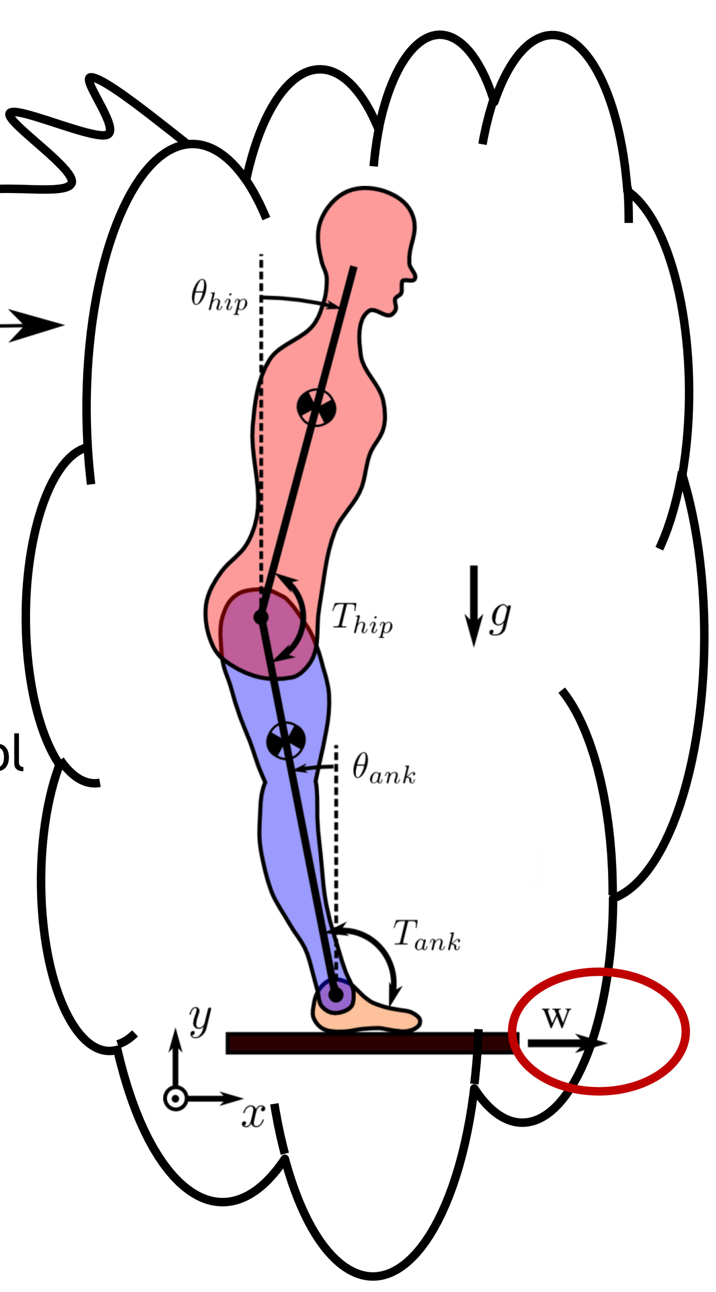


Fig. 2. Simple model of human balance control

$$\boldsymbol{x} = \begin{bmatrix} \theta_{ank} \\ \dot{\theta}_{ank} \\ \theta_{hip} \\ \dot{\theta}_{hip} \end{bmatrix}, \quad \boldsymbol{T} = \begin{bmatrix} T_{ank} \\ T_{hip} \end{bmatrix}$$

Feedback Law is:

$$\begin{bmatrix} T_{ank} \\ T_{hip} \end{bmatrix} = -\begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} \\ K_{21} & K_{22} & K_{23} & K_{24} \end{bmatrix} \begin{bmatrix} \theta_{ank} \\ \dot{\theta}_{ank} \\ \theta_{hip} \\ \dot{\theta}_{hip} \end{bmatrix}$$

The DIP equations of motion were linearized at the upright balance position, resulting in a closed loop system equation.

Test Data

$$\dot{\boldsymbol{x}} = (A - BK)\boldsymbol{x} + B\boldsymbol{v} + \boldsymbol{W}$$

A, B are system property matrices
K is a 2×4 controller matrix
$\boldsymbol{W}$ and $\boldsymbol{v}$ (controller noise) modeled by Brownian motion.

Model parameters were obtained from the literature [2]. The stochastic system was simulated using the Euler-Maruyama method for 100 seconds with a fixed step of 0.1 (ms). Angles, angular velocities, and joint torques were sampled at a rate of 100 Hz to simulate the typical instrumentation for human motion analysis.

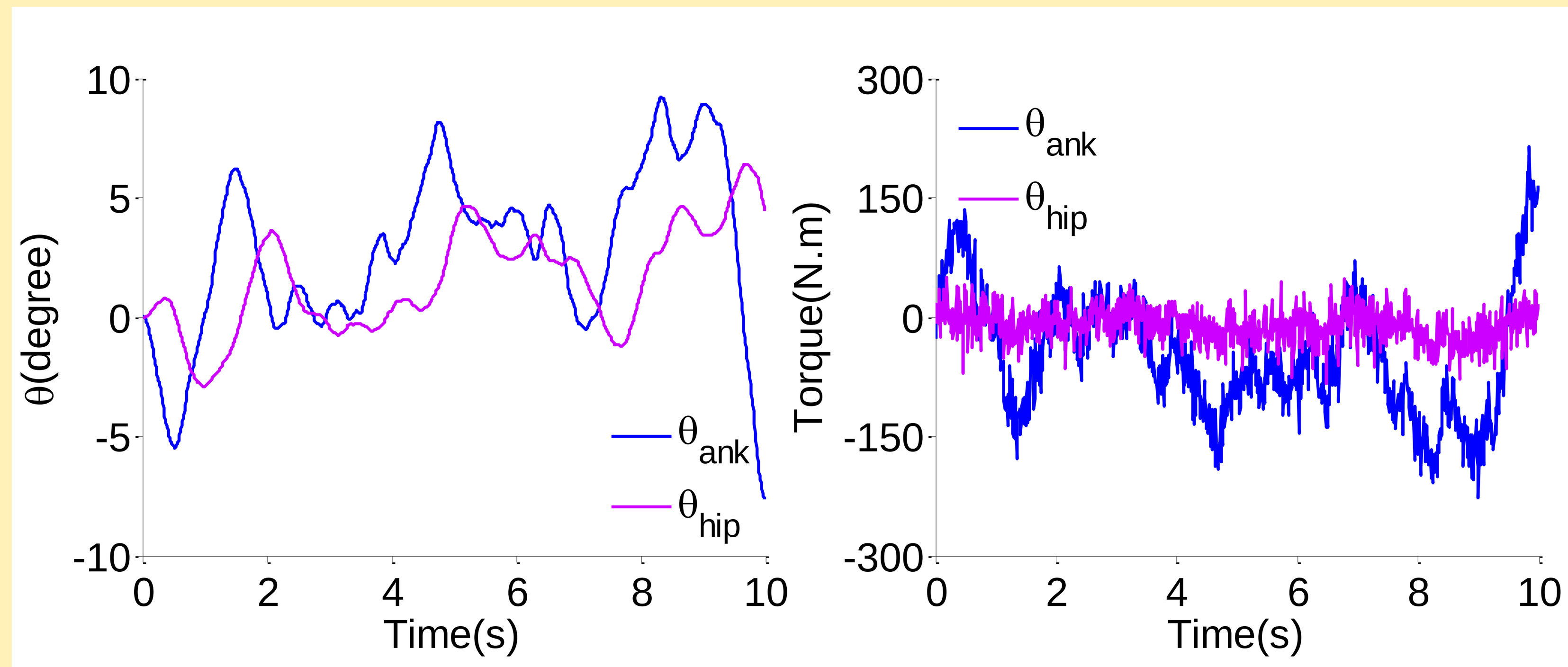


Fig. 3. Example of simulated joint angles (left) and joint torques (right)

Gain Estimation

Gains were estimated by linear least squares, Averages and standard deviations were computed over 100 Brownian paths.

Result

When data were used from quiet standing (W=0) or very small perturbations, the estimated gains were biased. At realistic amounts of perturbation, there was no bias and the standard deviation was small.

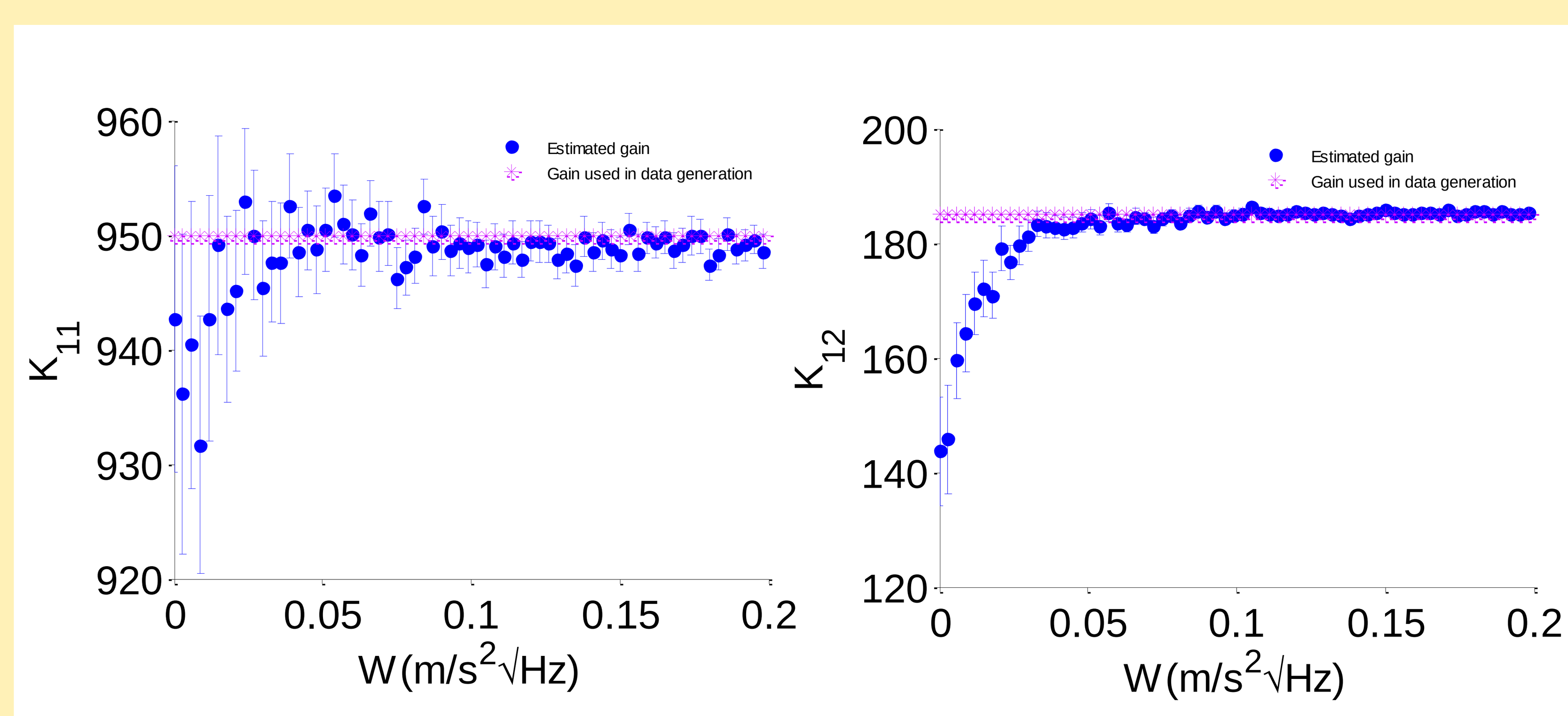


Fig. 4. Estimated feedback gain K_{11} (left) and K_{12} (right) for different platform perturbations

Conclusion

- ❑ For quiet standing the estimated gains were biased toward the inverse of plant dynamics.
- ❑ As the perturbation magnitude increased, the biased decreased along with random error.
- ❑ Direct approach can be applied to identify feedback control gains when perturbations are large enough.

References

1.Van der Kooij H, et.al..J Neurosci Mech 145, 175-203, 2005.
2.Park S, et.al..J Exp Brain Res 154, 417-427, 2004.

Acknowledgment
The work was supported by the State of Ohio through the Wright Center for Sensor Systems Engineering.