Can a bicycle be balanced using an optimal feedback control mechanism that ignores the sensorimotor delay?

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Abstract:

A rider balances her bicycle by means of control actions computed by the central nervous system (CNS) and executes these actions via her body’s neuromuscular system. A biologically realistic model for bicycle balance control must take into account the biological constraints of the neuromuscular system. In the present study, we focus on the sensorimotor delay (SMD), which is the time between the registration of sensory feedback and the delivery of the control action (Crevecoeur and Gevers (2019)). From empirical studies (Scott (2016)) we know that the SMD is between 60 and 100 ms. This study has two objectives: (1) to investigate the biological plausibility of a model of bicycle balance control with respect to SMD and, (2) to formulate a prediction component (implemented in the CNS) and evaluate whether it successfully deals with bicycle imbalance caused by a SMD that is too long.

Figure 1. Framework of the bicycle balance control enhanced by the SMD. The mechanical system (in red) is controlled by the computational system, CNS, (in blue). The CNS receives the sensory information (in green) and in response generates optimal motor control actions (in black). The motor control actions are delayed by a shift register.
The biological plausibility of the bicycle balance control with respect to the SMD (see Fig. 1) was investigated in the context of the stochastic optimal feedback control (OFC). Concretely, we exploited the framework of bicycle balance control derived in Maris (2022). The balance control comprises two components, the mechanical and the cognitive. The former one consists of the plant, the bicycle and the rider’s body, and obeys the laws of mechanics. The cognitive component refers to the biological mechanisms that the central nervous system (CNS) exploits to respond to the physical principles. The CNS uses an internal forward model to control the mechanical system. It receives the sensory information and in response generates two optimal motor control actions: (1) steering and (2) leaning the upper body. Both the sensory input and the motor output were corrupted by noise. The SMD was simulated by a shift register and it could be introduced either on the motor output or the sensory input. In this study, we introduced the delay in the motor output and we assumed an optimal CNS. All simulations were performed using the benchmark double pendulum (BDP) for studying the bicycle’s passive dynamics and the double pendulum as described by Meijaard et al. (2007). Regarding the bicycle’s passive dynamics, the linearized EOM are derived for a bicycle and a rider with no upper body. On the other hand, the linearized EOM of the double compound pendulum model the interactions between the upper body and the rear frame, including the lower body.

For evaluating the biological plausibility of a model of bicycle balance control, we must take into account that, even while cycling without external perturbations, there is variation in the lean and steering angles. This variation reflects the inevitable sensorimotor noise (SMN) and the control actions dealing with its consequences (Maris (2022)). Every realistic model therefore must have a random component that produces lean and steering angle variation that approximates the variation observed during actual cycling in a perturbation free environment. In our simulation study, we independently manipulated SMD and SMN amplitude (SMNA) and evaluated whether there are (SMD,SMNA) pairs that produce realistic lean and steering angles. In this way, we determined the maximum SMD that produces realistic steering and lean angles, and we observed that this exceeded the minimum SMD measured in humans.

We next investigated whether SMD-induced stabilization failure could be repaired by adding a prediction component to the CNS. There are several ways to build such a prediction component (Crevecoeur and Gevers (2019)), and in our simulation study we focused on linear prediction (Makhoul (1975)) using the CNS’s internal model. We will compare the performance of the different prediction components with respect to how well they can stabilize the bicycle for a wide range of SMDs and SMN characteristics.

References


