Balance Assist Bicycle Reduces Undesired Motions and Fall Probability When Subjected to Disturbances

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1 INTRODUCTION

The lack of bicycle self-stability at speeds below normal cruising speeds contribute to falls due the need for acute rider balance control. We have developed a balance assisting bicycle that uses a custom electric motor to apply a steering torque in parallel with the rider's steering actions. The motor is controlled by a simple control algorithm based on feedback from a rate gyroscope that measures vehicle roll angular rate. Applying a steering torque in the same direction and proportional to the rolling rate can lower the speed range at which the bicycle feels self-stable to the rider. We hypothesize that making the bicycle stable at lower speeds will reduce the control action needed from the rider in basic balancing tasks and that use of such a system may reduce falls. We have developed three comprehensive experiments to assess the effectiveness of the balance assist effects. In the first experiment, we both distract the rider and apply small disturbances via the steering motor during straight line balancing. In the second experiment, we apply increasingly large perturbations to the handlebars via computer controlled ropes while riding on a treadmill at low speeds. In the final experiment, we perturb straight line riding via a kickplate, which slides the ground out from under the front wheel of the bicycle, to see differences in the recovery response with and without balance assist enabled.

2 METHODS

To design the controller, we utilized the linear Carvallo-Whipple bicycle model from [1]. The states are the roll angle ϕ and steer angle δ along with their time derivatives and the inputs are roll torque T_ϕ and steer torque T_δ. The state $\mathbf{A}$ and input $\mathbf{B} = \begin{bmatrix}\mathbf{B}_\phi & \mathbf{B}_\delta\end{bmatrix}$ matrices are functions of the equilibrium forward speed v. The applied steering torque T_δ is the sum of the (h)uman and (m)otor torques, with the motor torque following a proportional roll rate feedback law scheduled by speed, similar to that shown in [2]:

$$T_\delta = T_\delta^{\mathrm{h}} + T_\delta^{\mathrm{m}} = T_\delta^{\mathrm{h}} - k_{\dot{\phi}}(v - v_{\mathrm{weave}})\dot{\phi} \tag{1}$$

where v_{weave} is the bicycle's open loop weave critical speed. This gives the closed loop model with the automatic control:

$$\begin{bmatrix}\dot{\phi}\\ \ddot{\phi}\\ \dot{\delta}\\ \ddot{\delta}\end{bmatrix} = \left(\mathbf{A} - \mathbf{B}_\delta \begin{bmatrix}0 & k_{\dot{\phi}}(v - v_{\mathrm{weave}}) & 0 & 0\end{bmatrix}\right)\begin{bmatrix}\phi\\ \dot{\phi}\\ \delta\\ \dot{\delta}\end{bmatrix} + \mathbf{B}\begin{bmatrix}T_\phi\\ T_\delta^{\mathrm{h}}\end{bmatrix}. \tag{2}$$

The gain $k_{\dot{\phi}}$ can be selected such that the eigenvalues of Equation (2) have negative real parts for a range of low riding speeds, making the bicycle stable.

We developed a series of three experiments, Figure 1, to assess whether stabilizing the bicycle is beneficial in safety critical scenarios:

Experiment 1 (E1) Comparison of 18 older and 14 younger adults in straight riding when 1) looking over their shoulder and 2) subjected to steer motor induced perturbations with assist on and off. We measured the standard deviation of steer and roll motions post disturbances.

Experiment 2 (E2) Twenty-six young adults were subjected to externally applied and measured handlebar torques of varying magnitudes while riding on a treadmill at speeds of $6\,\mathrm{km\,h^{-1}}$ to $10\,\mathrm{km\,h^{-1}}$. We determined the magnitude of perturbation required to cause them to fall with the balance assist system on and off. We logged the order of perturbations and applied impulse as well as the bicycle state at the time of perturbation.

Experiment 3 (E3) We subjected 11 participants riding at $12\,\mathrm{km\,h^{-1}}$ to lateral pulse-like perturbations at the front tire contact patch as they rode over a kickplate. We measured the standard deviation of the steer, yaw, and roll motions post disturbance with assist on and off.

(a) E1: Course layout (left) and GNSS traces (right).

(b) E2: During (left) and after (right) handlebar perturbation.

(c) E3: Just after leftward front wheel kick.

Figure 1: Representative images from each experiment.

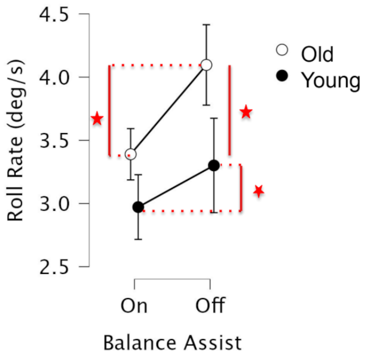
We then apply multivariate linear regression to the performance metrics derived from each experiment (ANOVA in E1 & E3 and logistic in E2) and investigated whether the balance assist system reduces response motions (E1 & E3) or the probability of falling (E2).

3 Results

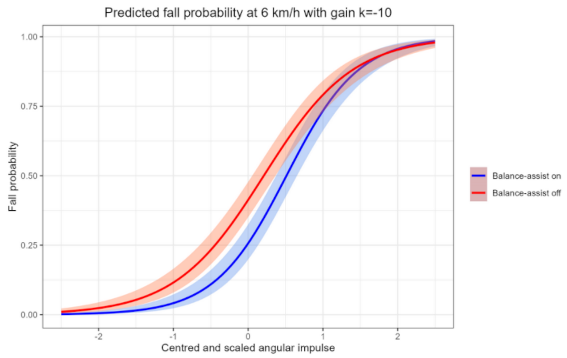
In E1, we found that the standard deviation of the roll rate during straight riding is reduced when the balance assist system is turned on for both young and old participants. In E2, the probability of falling is significantly reduced while riding at $6\,\mathrm{km\,h^{-1}}$ when the balance assist system is on. There is also a reduction in probability at $10\,\mathrm{km\,h^{-1}}$, but the effect was not statistically significant ($p = 0.7$). In Experiment 3, we found that the standard deviation of steer angle, roll angle, and yaw angle are all significantly reduced post perturbation when the balance assist system is on.

4 CONCLUSIONS

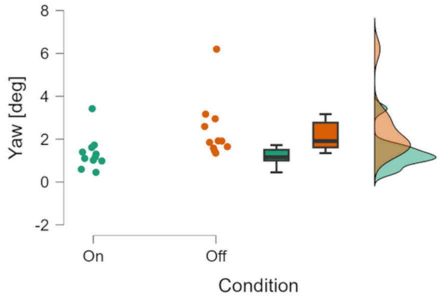
The balance assist system, driven by roll rate feedback steering control, stabilizes the riderless bicycle at speeds greater than approximately $4\,\mathrm{km\,h^{-1}}$, which is much lower than the uncontrolled



(a) E1 Results: Roll rate standard deviation reduction. Stars indicate significant difference.



(b) E2 Results: Fall probability as a function of mean centered and normalized perturbation impulse.



(c) E3 Results: Yaw angle standard deviation reduction.

Figure 2: Representative results from each experiment.

minimum stable speed of about 18 $\mathrm{km\,h^{-1}}$. The bicycle is rideable and we show that motions resulting from disturbances and distractions are reduced with the system on. We also show that the probability of falling is significantly reduced at low speeds when the system is on. Given that large steer and roll motions correlate to reduced rider control authority and that many single actor falls occur at low speeds [3], we project that wide use of a balance assisted bicycle may reduce falls and thus injuries.

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