Bicycle balance assist system reduces roll and steering motion for young and older bicyclists during real-life safety challenges

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ABSTRACT

Bicycles are more difficult to control at low speeds due to the vehicle's unstable low-speed dynamics. This issue might be exacerbated by factors such as aging, disturbances, and multi-tasking. To address this issue, we developed a second prototype 'balance assist system' with Royal Dutch Gazelle and Bosch eBike Systems at Delft University of Technology, which includes an electric motor capable of providing additional steering torque to that of the rider. We conducted a study with 18 older and 14 younger cyclists to first examine the effect of aging, disturbances, and multi-tasking on cycling at lower forward speeds, and evaluate the effectiveness of the system in improving the self-stability of the rider-bicycle system while facing these challenges.

The study consisted of two scenarios: a single-task scenario where participants rode the bicycle on a marked narrow straight-line track, and a multi-task scenario where participants performed a shoulder check task and followed visual cues while tracking the straight-line. We introduced handlebar disturbances using the steer motor also in half of the trials in both scenarios. All trials were repeated with and without the balance assist system. We calculated the bicycle mean magnitude of roll and steering rate – as indicators of bicycle balance control and steering effort, respectively – and the rider's mean magnitude of lean rate with respect to the ground to investigate the effect of the balance assist system on rider's lateral motion.

Our results showed that aging, disturbances, and multi-tasking increased the roll rate, but the balance assist system was able to significantly reduce it. The effect of the balance assist system in reducing the roll rate in all conditions was more significant in older cyclists. Disturbances and multi-tasking increased the steering rate, which was successfully reduced by the balance assist system. Aging did not significantly affect the steering rate. The rider's lean rate was not significantly affected by age, disturbances, or the balance assist, indicating that the upper body plays a minor role when riders have good steering control authority.

Overall, our findings suggest that lateral motion and steering effort can be affected by age, multi-tasking (distractions), and handlebar disturbances which can endanger cyclists' safety, and the balance assist system has the potential to improve cycling safety and reduce the incidence of single-actor crashes. Further investigation on riders' contribution to control actions is required.

INTRODUCTION

Cycling is an eco-friendly means of transport that enhances the healthy lifestyle and is favored by many people. Over the past decade, there was an increasing societal interest in electric bicycles (e-bikes) where the number of e-bikes sold in Europe increased from 0.5 million in 2009 to 3 million in 2019 (Statista). E-bikes enable riders to cycle for longer duration and distance by reducing physical fatigue (Hoj et al., 2018). However, with increased numbers of e-bikes, bicycle accidents due to inadequate steering and balance control by older cyclists have increased (Lefarth2021; Berk2022).

Bicycles are statically unstable but under certain conditions, e.g., higher forward speeds and rider's control, can become stable (Astrom et al., 2005). In The Netherlands in 2020 70% of cycling crashes were reported to be single-actor with slippery surfaces and loss of balance as the main causes (Krul et al., 2022). Bicycle balance control requires a mixture of passive (bicycle's self-stability) and active (rider) control to ride the bicycle in a stable balance state such that the rider-bicycle system could maintain or quickly restore if subjected to disturbances. Bicycle dynamics may be affected by a lot of factors, such tyre characteristics (Dell'Orto et al., 2022), road unevenness, and wind disturbance (Schwab et al., 2018). Therefore, keeping the bicycle balanced (especially at low forward speed), pedaling, and steering requires continuous physical and cognitive effort. In this context, an additional external disturbance makes it more challenging for the rider to be balanced ((SWOV, 2017); (Schwab et al., 2018); (Afschrift et al., 2022)).

Balance control in older adults due to the degradation in sensory and motor organs is poorer than young adults ((Alizadehsaravi et al., 2020); (Afschrift et al., 2022)). Older cyclists have higher roll rate and steering motion compared to middle-aged cyclists in low speed and multi-task cycling, which indicates age-induced difficulty to control the bicycle's inherent unstable motion (Kovácsová et al., 2016). In addition to aging, variety in riding skills also leads to different bicycle postural control strategies (Cain et al., 2016) which might in turn also vary in response to internal and external disturbances. To improve safety, older adults, unskilled cyclists, and regular cyclists in challenging situations could benefit from an enhanced balance control.

After the first prototype presented in (Nieuwenhuizen and Schwab, 2017), we developed the second prototype balance assist bicycle together with Royal Dutch Gazelle and Bosch eBike Systems aiming to increase safety by enhancing the bicycle's ability to not easily become unstable (i.e., robust balance control). We hypothesized that external disturbances and multi-tasking affect the bicycle motion and that our balance assist system improves the stable damping response in steer and roll rate. We also hypothesized that older cyclists have less lateral control authority than younger cyclists and balance assist system is more effective for older participants. Reduction in roll rate (lateral motion) and steering rate variables are expected based on the reduced demand for compensatory and acute steering control, respectively, as balance assist system applies enough control input to maintain or regain the bicycle's balance.

METHODS

The aim of the study was to evaluate the effects of the balance assist system in situations that cycling is challenging especially for older cyclists.

Design and implementation of the controller

We first simulated the uncontrolled benchmark bicycle motion with a rigid rider (Meijaard et al., 2007) and replicated the results that in forward speeds between 1 to 10 (m/s) the bicycle is laterally unstable, except for a range between about 4 to 6 (m/s) (this range depends on the bicycles and rider's dimensions and physical properties) that the bicycle is laterally self-stable (Meijaard et al., 2007). We simulated the benchmark bicycle motion with a rigid rider and then added the speed dependent feedback control. Our control aim was to stabilize the system at all forward speeds and the capacity to reject disturbance using a controller with the concept of the "steer-into-the-fall" (Schwab et al., 2008). In an uncontrolled bicycle the weave mode is unstable at low forward speed (positive real parts of the eigenvalues shown with rigid cyan line in Figure 1) and the capsize is unstable at higher forward speed (positive real parts of the eigenvalues shown with rigid dark blue line in Figure 1). We take the bicycle roll and steering angles and rates to be the states of the system with a 'zero-roll rate' setpoint, and steering torque is an output of the controller (and thus input to the bicycle-rider system). We applied control gains on roll rate and steering angle feedback at low forward speeds ($<$4.7 (m/s)). We manually tuned the gains to maximize stability across much of the speed range while also minimizing required steering torque. We showed that with this controller the region of stability in the bicycle shifted to lower forward speeds (1.3 (m/s)) and at higher speeds bicycle motion became marginally stable compared to an uncontrolled motion (Figure 1). Since simulation model is a simplification that does not consider the rider's relative motion to the bicycle, slightly different results are to be expected in real scenarios.

Instruments

The participants rode a Gazelle step-through city electric bicycle (Arroyo C8 electric), that has been modified as a balance assist bicycle with a custom direct drive steering motor embedded in the headtube

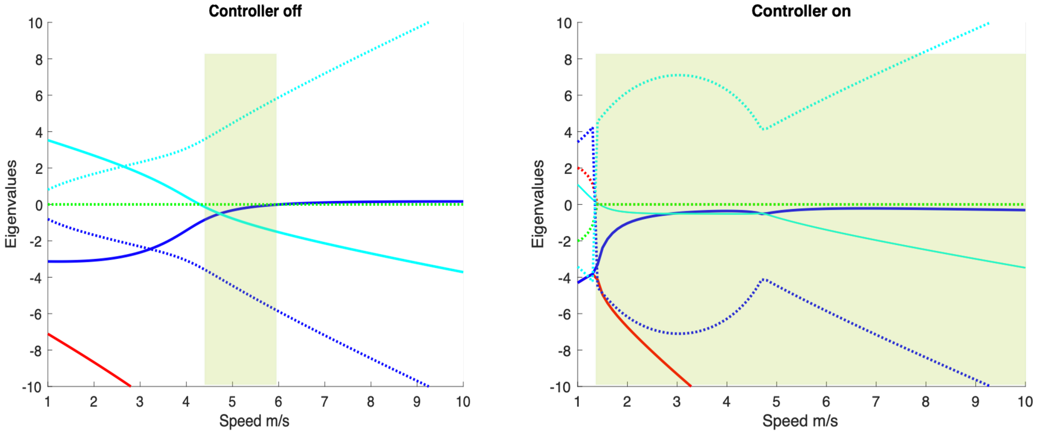

Figure 1. Eigenvalues from the linearised stability analysis for the bicycle, where the solid lines correspond to the real parts of the eigenvalues and the dashed line corresponds to the imaginary part of the eigenvalues, in the forward speed range of 1 to 10 (m/s) without (left panel) and with (right panel) the controller.

(Figure 2). This motor is meant to provide an additional torque between the headtube and the steer tube, helping the rider in the steering maneuver. We instructed the participants to cycle with a self-selected 'constant' speed (Appendix 1) in the range of 2 to 5 (m/s) on eco mode (lowest propulsion assist level), to take advantage of the bicycle's instability at low speeds.

With balance assist prototype 2, the bicycle's forward speed, roll and steer angle and rate are known. Balance assist bicycle is equipped with a wheel speed sensor on rear wheel, Bosch steering angle sensor at the steering tube with 0.1-degree absolute physical resolution and 100 (Hz) sampling rate, and data acquisition plus control boards in its rear luggage rack. The steer motor applies up to 7 (Nm) torque between the rear frame of the bicycle and the steering tube. We tuned the control gains of a simulated control algorithm to stabilize the balance assist bicycle at much lower speeds by generating a corrective steering torque. The steer motor directly applies torque to the steer to stabilize the bicycle's roll rate at 0 (deg/s) setpoint.

We evaluated the effectiveness of the balance assist system in young and old cyclists by simulating a series of conditions comparable with real-life cycling challenges. To directly investigate the rider's motion, a 3-axis IMU sensor (Shimmer research Ltd, Ireland) was mounted on the spine at the T7 level by an elastic strap on the back of the participant (Appendix 1, Figure S1) prior to performing the experiment.

Participants

32 participants (18 old, 67±4 years old, 174±8 (cm), 83±14 (kg), 6 females; and 14 young, 23±2 years old, 179±10 (cm), 71±12 (kg), 3 females) participated in this study. The participants were recruited by advertisements. All participants signed a written consent form and were able to cycle and had no balance disorders or history of injury or fall caused by instability over the last year. The Human Research Ethics Committee of the Delft University of Technology (The Netherlands) approved the experiments (Letter of Approval 2080).

Experimental procedure

All participants first cycled for 2-5 minutes to get familiarized with the bicycle with and without the balance assist system (blind setup), and to reduce the habituation effect throughout the experiment. Then participants performed 16 trials divided in two scenarios (single- and multi-task cycling; Appendix 1, Figure S2).

Single- and Multi-task Scenarios

A common and simple task often experienced during natural cycling is tracking a constant heading without deviating laterally from a straight path, for example when you ride along a straight cycle path alongside a fellow cyclist, along a narrow cycle path, or close to a cycle path edge. To mimic this task, we asked

Figure 2. Second prototype Balance assist bicycle at Delft University of Technology in collaboration with Royal Dutch Gazelle and Bosch eBike Systems. The steer motor and the data acquisition box (DAQ) are annotated in the picture.

our participants to ride at a constant self-selected low speed (2 to 5 (m/s)), along a 30 (m) straight line highlighted with a 5 (cm) width road-tape on the ground.

A common multi-task scenario was simulated by asking the participants to do a shoulder check task and follow instruction corresponding to the identified visual cues while tracking the above-mentioned line. The instruction was to look back at the starting point over their preferred shoulder the moment they reached the red cone in the middle of the track. At the starting point the researcher was holding up a cone randomly in her left or right hand. Participants were instructed to identify that direction and lift/place back their corresponding hand off/on the handlebar while following the track as closely as possible.

Each scenario includes four conditions with one repetition, resulting in a total of eight trials (2 Balance assist states (on/off) x 2 Disturbances states (on/off) x 2 repetition) per scenario. All participants have data available for the single-task scenario. However, due to system malfunction under the high load of self-induced perturbation using the steer motor in hot weather, four participants (3 older and 1 young) had missing data in the multi-task scenario and were excluded from multi-task scenario statistical analysis. For the rider's upper body lean rate, data from 24 participants were available, including 6 young and 18 older participants.

Disturbances

In half of the trials (in total and per scenario) participants were subjected to small disturbances induced by the steering motor when the balance assist system was (de)activated (Appendix 1, Figure S3). The purpose was to evaluate the bicycle behavior when an unwanted disturbance applies to the bicycle and causes difficulty in control, such as when you hit a bump in the road (short-duration) or front rack cargo or the wind gust pulls the steer in an undesired direction (long-duration). The disturbances were implemented by 3 square wave pulses with random intervals resulting in ∼1.2 (Nm) steering torque. This perturbation is significant because steer torques during straight-line riding tasks are less than 5 Nm (Moore, 2012). The disturbances began one second after the forward speed reached 2 (m/s) for the first time in that trial. The durations of the disturbances were 0.5 (s) and 1 (s) in single-task and multi-task cycling, respectively.

Data Analysis

We collected time series data from various sensors, including the steering angle sensor, the rear frame IMU, and the IMU placed on the rider's torso. We analyzed the data to obtain the bicycle's steering rate, roll rate, and rider's upper body lean rate as the outcome measures (dependent variables).

To study the effect of different conditions on these dependent variables, we first extracted and segmented relevant data from the sensors, along with forward speed and yaw motion data. We manually identified the start of cycling when the forward speed increased from 0 (m/s). We then divided the time series data into two phases: the transient phase when accelerating from zero to a steady-state phase where the speed was approximately constant until the end of the track. For analysis, we used the steady-state phase of the time series data as a segment of interest.

To determine the start indices for each segment of interest, we used the first index at which forward speed reached 1.5 m/s in the accelerating phase. To determine the end indices for each segment of interest, we used two criteria: the first index at which either forward speed reached 1.5 m/s in the decelerating phase or the absolute difference in yaw rate was greater than or equal to 4, indicating a change in cycling direction at the end of the cycling track. We chose 4 deg/s yaw rate as a threshold for starting to turn after visually inspecting all trials.

We updated the start and end time points to segment all signals from the bicycle and rider's IMUs and the steering angle sensors. To reduce noise and high-frequency components in the signals, we applied a low-pass Butterworth filter with a cutoff frequency of 25 Hz and a second-order Butterworth filter on the roll rate and steer rate signals. We also detrended the resulting filtered signals by subtracting their mean values.

We then calculated the mean absolute steering rate, roll rate, and lean rate of the time-series data over each segment that represented an approximate steady-state traversal. Finally, we calculated the average of two repetitions per condition to reduce the effect of randomness in balance control.

Note that, desirably, we wanted two repetitions per condition. However, in a few cases, due to malfunctions, the system did not apply the perturbation, resulting in trials being labeled as not disturbed. For the analysis, we reported the average of the maximum number of repetitions per condition. If subjects had no trials performed for a particular condition, we excluded them from the analysis. For illustration purposes, we included representative time series of bicycle motion data of all conditions in multi-task scenario in Appendix 1, Figure S5.

Bicycle's steering motion; steering rate

We quantified the steering rate by the mean absolute steering rate in (deg/s). The steering rate is the rate of change of steering angle around the steer axis δ (Appendix 1, Figure S6). Higher steering rate correlates to the total (rider + motor) steer control effort to stabilize the vehicle. Since we have not measured the rider's steering effort separately, the results here is a summation of the rider and the steer motor's contribution to steering motion. We assumed that a decreased steering rate indicates that the rider needs to put less steering effort to maintain the bicycle's balance control, in those cases when the balance assist system is switched on. If the steering rate is higher in the condition where the balance assist is on compared to when it is off, we cannot draw a strong conclusion on the rider's effort in motion control.

Bicycle's lateral motion; roll rate

We quantified the bicycle's lateral balance control by the mean absolute roll rate of the bicycle. The roll rate is the rate of change of angle of bicycle rear frame in lateral direction (YZ plane) or around the X (or forward) axis (Appendix 1, Figure S6). A lower roll rate indicates that the system is better damped and there is less oscillation around the vertical axis when the system is subjected to internal (noise in motor control) or external disturbances (steer motor).

Rider's lateral motion; lean rate

The IMU's Y axis was aligned with the participant's spine, X axis was vertical to Y in the frontal plane, and Z axis was vertical to Y axis in the sagittal plane (Appendix 1, Figure S1). We evaluated the rider's postural balance control by the lean rate defined as the rate of change of torso angle in Shimmer IMU XY plane or around the Z axis relative to the Earth. A well-behaved closed loop system will damp out disturbances quickly and not oscillate too much. Therefore, higher lean rate means that the rider has more oscillation and the rider-bicycle closed loop system is not damping the disturbances optimally.

Statistics

To evaluate the effects of the Balance assist system, Disturbances, and Aging on dependent variables (steering, roll, and rider's lean rate), we performed repeated measures ANOVA with Balance assist (on/off) and Disturbances (on/off) as within-subject factors and Aging as a between-subjects factor. In the case of a significant main effect, we investigated the interactions of effects, and if significant, post-hoc ANOVA was performed to test the effect of Balance assist on affected variables.

To evaluate the effects of Scenarios (multi-tasking) we performed the repeated measures ANOVA on dependent variables with Balance assist (on/off) and Scenarios (single-task/multi-task) as within-subjects, and Aging as a between-subjects factors on Undisturbed trials. Since the duration of disturbances was different in single- and multi-task cycling, to evaluate the effect of Scenarios, the disturbed trials were excluded for a fair comparison between two scenarios.

Finally, in case of effectiveness of the balance assist in improving the outcome measures, to gain insights into how the balance assist system affects each age group separately, we conducted a simple main effects analysis. We divided the data by age group and performed an ANOVA on each group to examine the effect of the balance assist system on the roll rate and steer rate.

We performed the statistical analysis in JASP (University of Amsterdam, The Netherlands) version 0.16, and $p<0.05$ was considered significant.

RESULTS

The results in Table 1 and 2, show the effects of Balance assist system, Disturbances and Aging on bicycle steering rate, roll rate, and the rider's lean rate. Table 3 shows the effect of Balance assist system, Scenarios (multi-tasking) and Aging on bicycle steering rate, roll rate, and the rider's lean rate for undisturbed conditions.

Table 1. The effects of Balance assist, Disturbances, and Aging on bicycle roll and steering and on rider's lean rate in single-task cycling.

Scenario 1; Single-task	Steering rate		Roll rate		Lean rate	
	F(1,30)	p	F(1,30)	p	F(1,17)	p
Balance assist	**39.273**	$<$ **.001**	**47.235**	$<$ **.001**	1.344	0.262
Disturbances	**31.198**	$<$ **.001**	**11.573**	**0.002**	0.509	0.485
Age	2.04	0.163	**6.675**	**0.015**	2.739	0.116
Balance assist $*$ Age	0.967	0.333	1.58	0.218	0.108	0.747
Disturbances $*$ Age	1.606	0.205	1.398	0.246	0.142	0.711
Balance assist $*$ Disturbances	0.348	0.560	0.853	0.363	0.117	0.737
Balance assist $*$ Disturbances $*$ Age	1.406	0.245	0.37	0.548	0.055	0.818

Table 2. The effects of Balance assist, Disturbances, and Aging on bicycle roll and steering and on rider's lean rate in multi-task cycling.

Scenario 2; Multi-task	Steering rate		Roll rate		Lean rate	
	F(1,26)	p	F(1,26)	p	F(1,17)	p
Balance assist	**10.556**	**0.003**	**21.377**	$<$ **.001**	0.293	0.595
Disturbances	**116.635**	$<$ **.001**	**60.394**	$<$ **.001**	2.152	0.161
Age	3.208	0.085	3.487	0.073	3.020	0.100
Balance assist $*$ Age	0.975	0.333	0.03	0.864	0.189	0.669
Disturbances $*$ Age	0.534	0.471	2.365	0.136	$2e-6$	0.999
Balance assist $*$ Disturbances	1.048	0.315	2.101	0.159	0.076	0.786
Balance assist $*$ Disturbances $*$ Age	2.281	0.143	1.904	0.179	0.076	0.786

Effects of Balance assist system, Disturbances, and Age per scenario

Effects of the Balance assist system, Disturbances, and Age in single-task cycling

In single-task cycling, a significant effect of the Balance assist system and Disturbances was found on the steering rate, without any interaction between main factors. The results indicate that the steering rate was higher in disturbed compared to undisturbed cycling ($t = 5.586$, $p < 0.001$, Cohen's $d = 0.987$), and that activation of the Balance assist system, regardless of age or disturbances, significantly reduced steering rate ($t = - 6.267$, $p < 0.001$, Cohen's $d = - 1.108$; Figure 3, Table 1).

Table 3. The effects of Balance assist, Scenarios, and Aging on bicycle roll and steering and on rider's lean rate in undisturbed trials.

Single- vs. Multi-task	Steering rate		Roll rate		Lean rate	
	F(1,26)	p	F(1,26)	p	F(1,15)	p
Balance assist	**34.681**	**< .001**	**38.275**	**< .001**	0.211	0.652
Scenario	**19.678**	**< .001**	**14.041**	**< .001**	0.514	0.484
Age	1.972	0.172	**6.686**	**0.016**	2.217	0.157
Balance assist ∗ Age	0.064	0.803	1.634	0.212	0.248	0.626
Scenario * Age	2.054	0.164	0.414	0.525	0.239	0.632
Balance assist ∗ Scenario	0.299	0.589	0.10	0.921	1.114	0.308
Balance assist ∗ Scenario ∗ Age	0.143	0.708	0.097	0.758	0.010	0.923

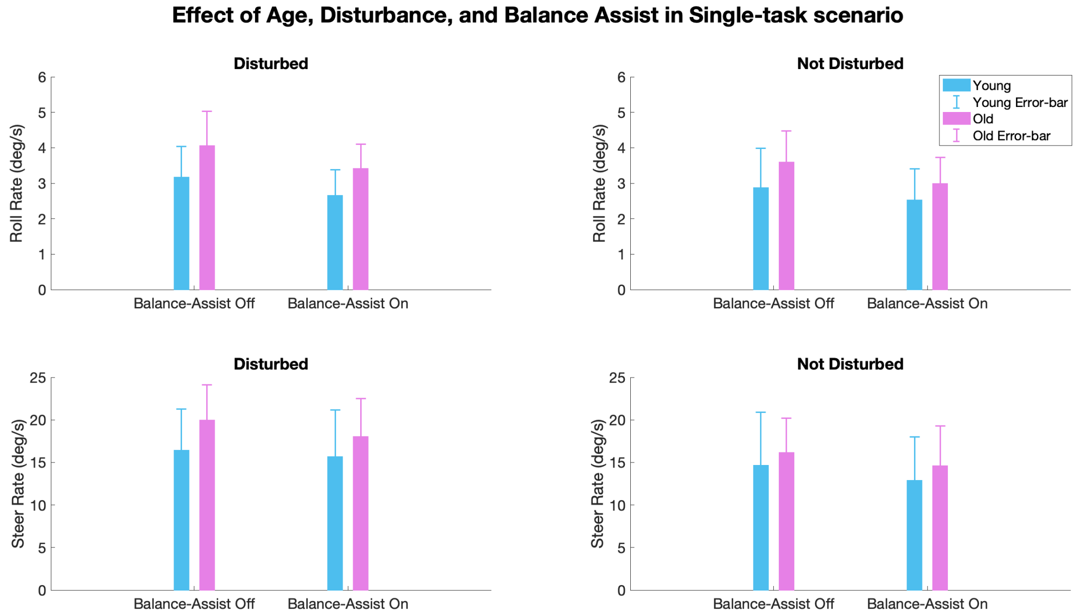

Figure 3. The effect of the Balance assist system on roll and steering rate in Single-task scenario. Bar chart with error bars show the mean and standard deviation of the roll rate and steer rate in disturbed and not disturbed conditions in presence and absence of the balance assist system in both age groups.

Regarding bicycle roll rate in single-task cycling, significant effects of the Balance assist system, Disturbances, and Age without any interactions between main effects were observed, (Figure 3, Table 1). Post hoc showed that roll rate was higher in disturbed compared to undisturbed cycling, and in older compared to younger adults (t = 3.402, p = 0.002, Cohen's d = 0.601, and t = 2.584, p = 0.015, Cohen's d =0.457, respectively). The balance assist system significantly reduced the roll rate (t = - 6.873, p <0.001, Cohen's d = - 1.215).

In straight line cycling there was not a significant effect of Age or Disturbances nor Balance assist on rider's lean rate (Table 1).

Effects of the Balance assist system, Disturbances, and Age in multi-task cycling

There was no significant effect of Aging on steering rate (Figure 4, Table 2). However, there were effects of Balance Assist and Disturbances on steering rate in multi-task cycling. While steering rate was higher in disturbed compared to undisturbed cycling (t = 10.566, p < 0.001, Cohen's d = 1.997), activation of the Balance assist system, regardless of age or disturbances, significantly reduced steering rates compared to deactivation (t = -3.249, p = 0.003, Cohen's d = -0.614).

The analysis of roll rate in multi-task cycling revealed significant strong effects of Disturbances and the Balance assist system on bicycle roll rate, with no significant effects of Age or any interaction between

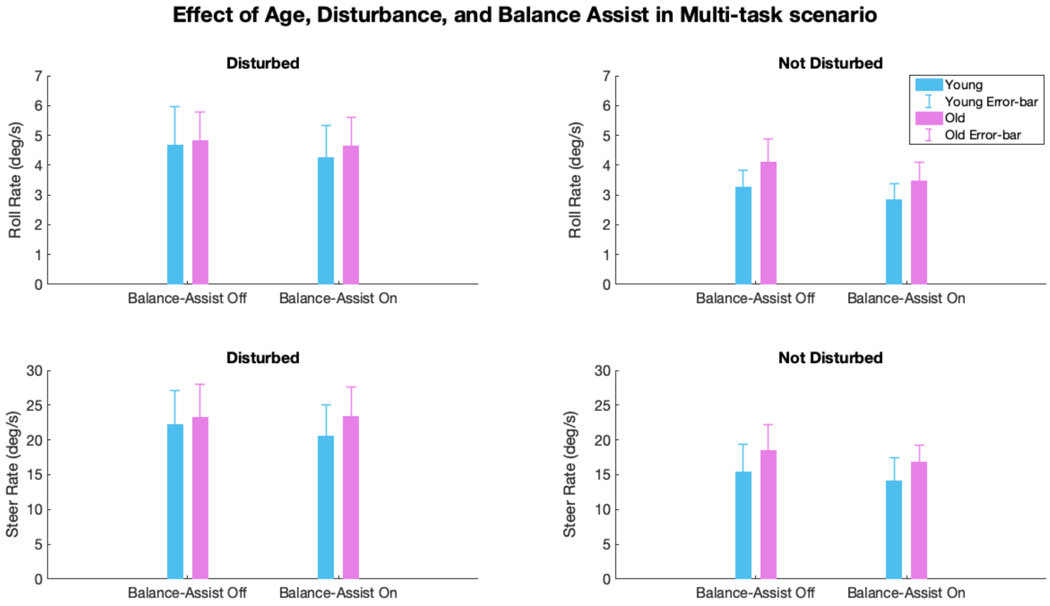

Figure 4. The effect of the Balance assist system on bicycle's roll and steering rate in Multi-task scenario. Bar chart with error bars show the mean and standard deviation of the roll rate and steer rate in disturbed and not disturbed conditions in presence and absence of the balance assist system in both age groups.

the main factors (Figure 4, Table 2). Post-hoc analyses showed higher bicycle roll rates in disturbed compared to undisturbed cycling (t = 7.771, $p < 0.001$, Cohen's d = 1.469), while activation of the Balance assist system resulted in significantly lower bicycle roll rates, regardless of age or disturbances (t = -4.623, p ¡ 0.001, Cohen's d = -0.874).

In multi-task cycling, there was not a significant effect of Age or Disturbances nor Balance assist system on riders' lean rate (Table 2).

Effects of Balance assist system, Scenarios, and Age (undisturbed cycling)

There was no significant effect of Aging, but there were significant effects of Scenario and the Balance assist system on the bicycle's steering rate (Table 3), without any interactions between the main factors. Post-hoc analysis showed that the steering rate during multi-task cycling was higher than during single-task cycling (t = 4.436, $p < 0.001$, Cohen's d = - 0.838), and that the steering rate was lower when the balance assist system was activated, regardless of scenario (t = -5.889, $p < 0.001$, Cohen's d = - 1.113).

Furthermore, there were significant effects of Aging, Scenario, and the Balance assist system on the bicycle's roll rate (Table 3). Post-hoc analysis showed that the roll rate was higher in older adults compared to young adults (t = 2.586, p = 0.016, Cohen's d = 0.489), and higher during multi-task scenarios compared to single-task scenarios (t = 3.747, $p < 0.001$, Cohen's d = 0.708). Regardless of Age and Scenario, the bicycle's roll rate was lower when the balance assist system was activated, compared to when it was deactivated (t = - 6.187, $p < 0.001$, Cohen's d = - 1.169).

There was not any effect of Aging, Scenario, or Balance assist system on rider's lean rate (Table 3).

DISCUSSION

At low forward speeds, a bicycle becomes very difficult to balance because the time-to-double of a bicycle's unstable motion can be as brief as 0.3 seconds (Hess et al., 2012). This difficulty is reflected in the very large motion variability observed during straight ahead cycling at low speeds (Moore et al., 2010). Applying external disturbances inevitably may cause growth in motion variability.

We aimed to reduce motion variability and thus rider control effort at low forward speed by introducing balance assisting torque. We expected reduced motion variability based on the reduced need for compensatory behavior (Alizadehsaravi et al., 2021) in the presence of assistive technology, as the bicycle states are known to the control unit. We designed and implemented the ‘steer-into-the-fall’ control algorithm that laterally stabilizes the bicycle at low forward speeds thus rejecting small perturbations. We evaluated the system’s effectiveness (regarding the lateral motion and steering effort) in response to real-life challenges experienced by the rider-bicycle system. We found that the balance assist decreased the steering rate (effort) and damped the lateral motion (roll rate) in all conditions in both age groups, indicating that less control effort may be required to steer and a better balance can be achieved on the bicycle using the balance assist bicycle. The rider’s lean rate did not change with age, disturbances, or balance assist, and this could be caused by the minimum role of the upper body to optimally maintain or regain the bicycle’s balance control with steering action when steer and lean are available (Sharp, 2008).

Overall, our results suggest that balance assist system can reduce unnecessary motions at low forward speed, during disturbances and multi-tasking and has potential to increase safety in challenging balancing conditions.

Balance assist and Aging

Our study found a significant effect of aging on roll rate and a trend towards higher steering rates among older participants, indicating reduced ability to control the bicycle’s rolling motion and suggesting that age may impact bicycle balance control. Regardless of age, our results showed improved bicycle balance control when the balance assist system was activated.

Recent research suggests that aging impacts the brain’s capacity for processing sensory inputs into motor actions (Moulton et al., 2022), and our findings suggest that the balance assist system may assist older cyclists by processing the bicycle’s states earlier than would occur in their central nervous system. This leads to a faster control action of damping lateral motion in the ‘older rider-bicycle’ system with balance assist system activated compared to when deactivated. Simple main effect tests showed that the balance assist system reduced roll rate in both single-task and multi-task cycling, with a greater effect on older cyclists roll rate (single-task; Older: $F = 51.547$, $P < 0.001$, Young: $F = 10.386$, $p = 0.007$ and multi-task; Older: $F = 14.113$, $p = 0.002$, Young: $F = 8.355$, $p = 0.014$). Furthermore, e-bikes reduce the physical effort for propulsion, but do not provide fatigue reduction in steering and balancing task. While steering in the long term may lead to fatigue and increase the risk of fall, especially in older cyclists (Weavil et al., 2018), the decreased steering effort using balance assist system is promising to reduce the risk of fall. The balance assist system assisted older adults more than young in reducing their steering effort (steering rate) in single-task (single-task; Older: $F = 44.759$, $P < 0.001$, Young: $F = 8.675$, $p = 0.011$), and all undisturbed trials among both scenarios (Older: $F = 42.335$, $P < 0.001$; Young: $F = 9.226$, $p = 0.01$).

In the context of combination of multi-tasking and disturbances, older and younger cyclists exhibited similar cycling behavior with respect to roll and steering rates. Although the balance assist system reduced these variables in both age groups, the reduction in roll rate was more significant in older adults than in younger adults. However, the reduction in steering rate in older cyclists was not statistically significant, whereas it was significant in younger cyclists (Older: $F = 4.160$, $P = 0.061$; Young: $F = 5.484$, $p = 0.037$). This could be due to delayed steering interruption of older adults in combination of multi-tasking (distraction) and disturbances, and a longer learning period might help them adapt to the system.

The increased number of single-actor bicycle crashes due inadequate balance control, especially in older cyclists, suggests that our system could induce balance control closer to young cyclists, potentially lead to safer cycling and reduce the number of age-related accidents. However, future research with larger sample sizes, various manoeuvres, and longer duration of cycling may be needed to confirm this trend and determine its significance.

Balance assist and Disturbances

Internal and external disturbances are challenges that cyclists encounter during cycling, being due to internal sensory and motor organs noise or environmental factors. Results showed that the disturbances increased the roll rate and reduced the lateral balance control authority. We found a reduced roll rate, which indicates an enhanced rider’s lateral ability to control the bicycle’s rolling motion, when using balance assist system.

In addition, disturbances also caused an increase in the steering rate (effort), in which balance assist system proved to be effective to decrease the steering rate. This indicates that using the balance assist system less steering action is needed to regain balance control after being subjected to disturbances. This could be beneficial for cyclists in the long term, as it can reduce physical fatigue. In addition, it may also foster a healthier lifestyle by allowing people to ride for longer distances. Our findings suggest that regardless of age and disturbances, amount of the steering actions to reach the perceived stability decreased by using the balance assist system.

Balance assist and Multi-tasking

In multi-task cycling, the steering rate (effort) and roll rate significantly increases, reflecting the higher cognitive and motor control demand of the additional tasks. Balance assist system showed to improve the lateral balance control and steering effort in multi-task cycling. Overall, our results suggest that multi-tasking increases the motion variability in cycling, while they are unavoidable in real-life situations, balance assist system can potentially improve the balance control and reduces the risk of undesired motion. Cyclists and especially older participants with lower cognitive and physical fatigue threshold could benefit from balance assist bicycle in long distance and duration riding.

Balance assist and cyclists' lateral balance control; lean rate

We did not observe any effect on the rider's lean rate. It might be due to the rider's choice not to lean when they can also steer to maintain the bicycle's balance, aligning with optimal control predictions (Sharp, 2008). Additionally, prior observations (Kooijman et al., 2009) and (Moore et al., 2011) give evidence that the rider keeps their upper body quite inertially stationary in straight riding even if the roll motion of the bicycle has relatively larger variability, i.e., it is much easier to roll the low inertia bicycle than the rider along with it for control purposes. This could explain the lack of lean rate changes we observe in this study. Alternatively, ineffectiveness of the balance assist system on the lean rate (torso lateral motion) could be explained by the fact that the balance assist controller does not measure or estimate the rider's state. While the controller succeeded in keeping the bicycle in an upright position with less lateral oscillation in presence of the balance assist system, it is not clear whether the riders were able to accept the control action induced by the steering motor without over-reacting. Therefore, further investigation is necessary to understand the rider's perception and intention.

Limitation and suggestion

There are some limitations in our study to note. We collected the older participants' data at a parking lot at the Den Haag Gazelle User Experience Center and the young participants at a parking lot at TU Delft where the surfaces of the road were slightly different (asphalt vs. cycling path bricks). However, collecting all data per participant in the same situation, eliminated the risk of false results. Note that the conclusion about balance assist system and aging was drawn by comparing the absolute changes in variables [variables activated - variables deactivated] per age group, so false results – differences in bicycle balance control between age groups – due to different road surfaces can be ruled out.

Moreover, in human-robot interactions, 'trust' is seen as a key to improve the operations and a feeling of safety (Goillau et al., 2003). Therefore, it is expected that when adapting to new assistive technologies, the positive effect of the assistive system is more pronounced when riders trust the technology and yield to the generated steering torque by the steering motor. Since there is no direct measurement of the rider's effort, again we cannot draw a strong conclusion whether that was by choice or the rider's put enough effort in optimizing the lateral motion variability. However, we have asked riders to perform trials in a consistent manner, therefore the variation in effort is not expected per participant and the results are due to balance assist action, rather than changes in riders' action.

We observed that 5 out of 18 older adults (all males) failed at least once in performing the first multi-task trial. In future studies estimating the lateral position of the bicycle and calculating the deviation of the rider-bicycle from the straight-line is suggested. It might be interesting to study the effect of gender on multi-task cycling to address adequate regulations for male older cyclists.

One of the common issues among our older participants was having a stiff neck which would not allow them to look over the shoulder without using their torso. The problem with that would be a higher variation of motion in older participants while their range of motion is limited compared to young participants and that influences the motion coordination and lateral balance. A small side mirror added to older participants' bicycles will potentially help to eliminate some of the hazards, but careful adaptation in identifying direction and distance of motion of other objects through the mirror is required.

CONCLUSIONS

Aging, disturbances, and multi-tasking are real-life challenges, and our study demonstrated that they can negatively affect cycling lateral balance and steering motion. Our balance assist system was shown to be effective in improving lateral balance by reducing lateral motion (indicated by the reduced roll rate) and reducing steering effort (indicated by the reduced steering rate). These effects were observed not only in single-task cycling but also in multi-task cycling, and in both age groups, both in the presence and absence of disturbances. The effects of the balance assist system were more significant among older cyclists in the majority of conditions, except for when disturbance and multi-tasking were combined. To further improve the effectiveness of the balance assist system in such a condition, adding human motion detection and estimation to the control algorithm could be considered.

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