Bicycle balance assist system reduces roll motion for young and old 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. Factors such as aging, disturbances, and multitasking can make it even more difficult to control.

Together with Royal Dutch Gazelle and Bosch eBike Systems we developed a second prototype 'balance assist system' at Delft University of Technology and implemented the 'steer-into-the-fall' control algorithm to produce the assistive steering torque. We evaluated the effectiveness of the balance assist at low forward speed on 18 old and 14 young cyclists in some conditions that might affect cycling safety, including handlebar disturbances, multi-tasking, and aging. Participants totally performed 16 trials (2 Scenarios (single- and multi-task) x 2 Balance assist states (on/off) x 2 Disturbances states (on/off) x 2 repetitions). In multi-task scenario, in addition to cycling on a straight line, participants performed a shoulder-check task and followed instruction corresponding to the identified visual cues. In half of the trials in both scenarios we implemented the disturbances through the steer motor. 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 to investigate the effect of the balance assist system on these variables.

Balance assist system decreased the bicycle's roll rate in all conditions. The decrease in roll rate was more pronounced in older adults during the single-task in both disturbed and undisturbed conditions. Balance assist decreased the steering rate, only in single-task cycling in both age groups, indicating less steering effort is required to maintain balance. The rider's lean rate with respect to the ground was not significantly affected by age, disturbances, or the balance assist. This could be caused by the minimum role the upper body plays when riders have good steering control authority. Overall, lateral motion and steering rate can be affected by age, disturbances, and multitasking, and the balance assist system shows that potential to improve cycling safety and reduce the number of single-actor crashes. More investigation on riders' contribution to control actions is required.

Keywords: balance assist, aging, bicycle, safety, balance control, assistive technology

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 (Lefarth et al. 2021; Berk et al. 2022)

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 as road unevenness, wind disturbance, and tyre characteristics (Dell'Orto et al. 2022). 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 multitasking affect the bicycle dynamics 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. a) and the capsize is unstable at higher forward speed (positive real parts of the eigenvalues shown with rigid dark blue line in Figure1.a). 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.b). 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 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.

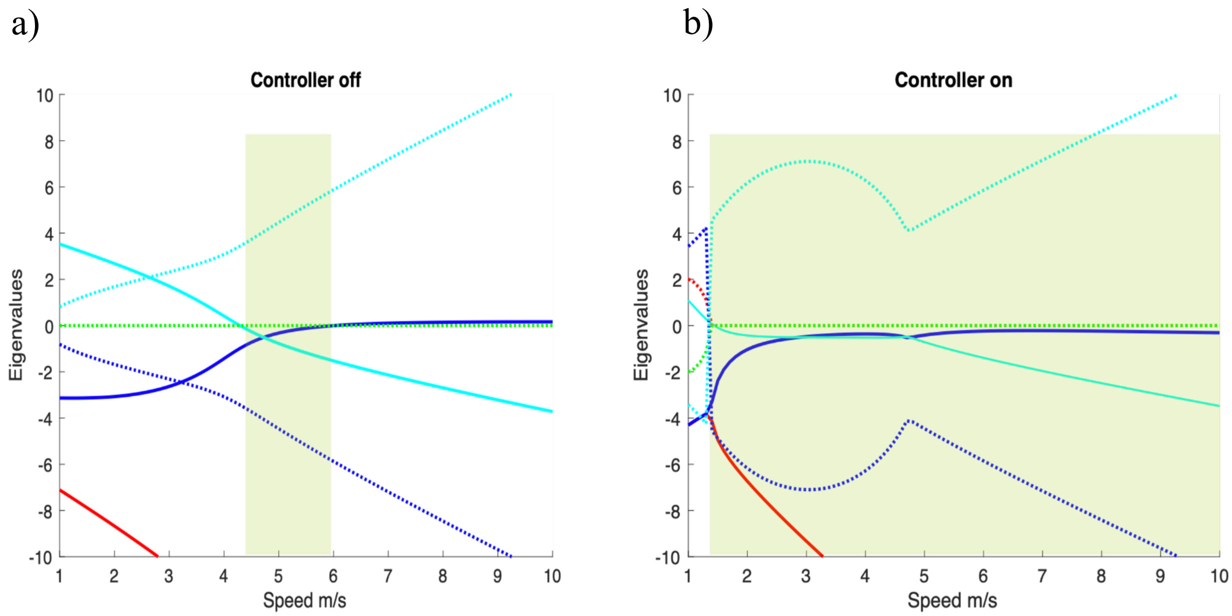

Figure 1. Eigenvalues λ from the linearised stability analysis for the bicycle, where the solid lines correspond to the real parts of the eigenvalues and the dashed line corresponds to the imaginary part of the eigenvalues, in the forward speed range of 1 to 10 (m/s) a) without and b) with the controller.

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 with 0.1-degree absolute physical resolution and 100 (Hz) sampling rate at the steering tube, and data acquisition and 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 Figure S1) prior to performing the experiment.

Figure 2. Second prototype Balance assist bicycle at Delft University of Technology in collaboration with Royal Dutch Gazelle and Bosch eBike Systems

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 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.

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 Figure S2).

Scenarios

Single-task scenario

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

Multi-task scenario

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 consists of 4 conditions with one repetition (balance assist on/off (2) * bicycle disturbed/not disturbed (2) * repetition (2). One older participant completed only the first scenario, 8 single task cycling trials, the rest completed all trials. For the rider's upper body lean rate, data from 24 participants were available (6 young 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 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 2-5 (s) intervals resulting in ~1.2 (Nm) steering torque. 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 analyzed the data from the steering angle sensor, the rear frame IMU, and the IMU placed on the rider's torso. The outcome measures (dependent variables) are defined as the bicycle's steering rate, roll rate, and rider's upper body lean rate, respectively.

Time series data were collected for the whole duration of the experiment. To study the effect of each condition on dependent variables, first we selected the trials based on the wheel speed sensor data. We defined the start of each trial when the forward speed increases from 0 (m/s). This includes the transient phase when accelerating from a stop and a steady state phase, featured by an approximately constant speed until the end of the track. In each trial, we segmented the data from the point when the rider accelerated and reached the forward speed of 1 (m/s) and ended the trial when the rider reached 30 m after the starting time point (Appendix Figure S4). We estimated the end time point of the trial by numerical integration of forward speed (using composite trapezoidal rule) with respect to time at 100 Hz sampling rate. Integration causes a drift in the integrated data and after visual observation we confirmed that the linear drift was consistent in all trials, therefore the measurement's systematic error can be ruled out. The estimated start and end time points were used to segment all signals from bicycle and rider's IMUs and the steering angle sensors. For final analysis all segmented data were resampled to 200 samples using Spline interpolation method. We calculated the mean absolute steering rate, roll rate, and lean rate of the resampled time-series data over each segment that represents a 30 m traversal. Finally, we calculated the average of two repetitions per condition to reduce the randomness in balance control. Two representative resampled time series steering and roll motion data per age group are shown in Appendix 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 Figure S6). Higher steering rate correlates to the total (rider + motor) steer control effort to stabilize the vehicle. However, 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 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 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 effect of 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-subjects, and Aging as a between-subjects factors. In case of a significant main effect, the interactions of effects were investigated and if significant, post-hoc ANOVA were performed to test for the effect of Balance assist. To evaluate the effects of Scenarios 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. Since the duration of disturbances was different in single- and multi-task cycling, the disturbed trials were excluded for a fair comparison between two scenarios.

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, and Aging on bicycle steering rate, roll rate, and the rider's lean rate simply for undisturbed conditions.

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, there was no effect of Aging but an effect of Balance assist system and Disturbances on steering rate were found, without an interaction between Balance assist system* Disturbances (Figure 3, Table 1). The results indicate that the steering rate was higher in disturbed compared to undisturbed cycling ($t = 2.062$, $p = 0.049$), and when balance assist system was activated, regardless of age or disturbances, steering rate was lower than when deactivated in single-task cycling ($t = -2.068$, $p = 0.048$).

In single-task cycling, there was an effect of Balance assist system and an interaction of Balance assist system * Aging on bicycle roll rate (Figure 3, Table 1). Post hoc showed that in both older and young participants roll rate was lower when balance assist system was activated compared to when deactivated ($t = -6.866$, $p < 0.001$; $t = -2.795$, $p = 0.037$, respectively). Moreover, when balance assist system was deactivated, older participants show higher roll rate than young participants ($t = 2.551$, $p = 0.047$), while when balance assist system was activated, there was no significant difference between young and older participants regarding the bicycle's roll rate ($t = 1.341$, $p = 0.379$).

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

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. The bold values indicate the significant effect, $p<0.05$.

Scenario 1; Single-task	Steering rate		Roll rate		Lean rate	
	F	p	F	p	F	p
Balance assist	**43.778**	**<0.001**	**4.278**	**0.048**	0.293	0.595
Disturbances	2.979	0.095	**4.254**	**0.049**	0.509	0.485
Age	4.042	0.054	1.125	0.298	3.020	0.1
Balance assist * Disturbances	0.154	0.698	1.540	0.225	0.076	0.786
Balance assist * Age	**5.804**	**0.023**	0.306	0.584	0.189	0.669
Balance assist * Disturbances * Age	6.264 e^-4	0.980	0.243	0.626	0.076	0.786

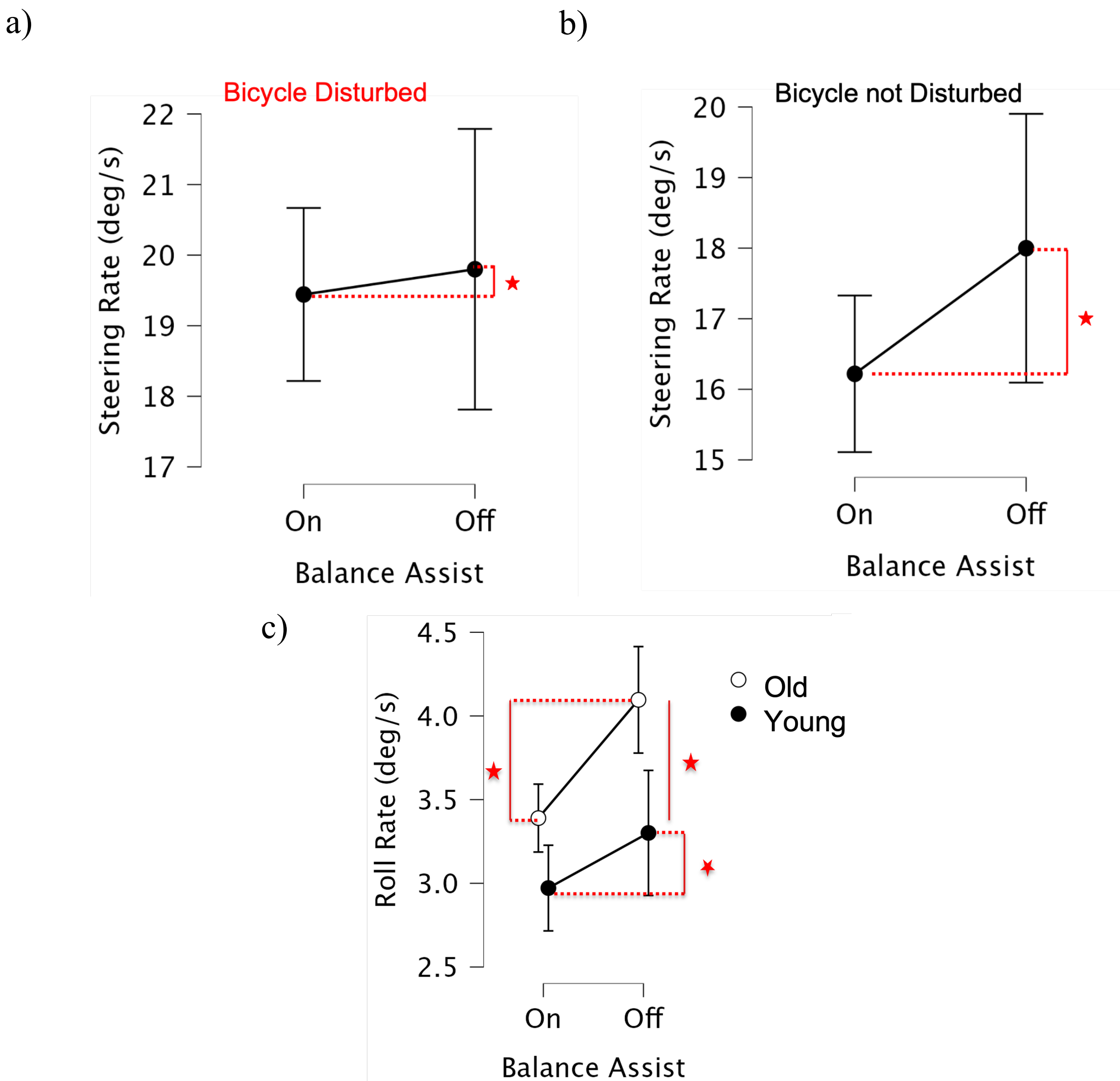

Figure 3. The effect of the Balance assist system on bicycle's steering rate in a) presence, b) absence of disturbances in single-task cycling averaged over both age groups, and c) on roll rate among young and old participants averaged over disturbed and not-disturbed trials. Average and error bars with 95% confidence interval of all subjects (in c) and within an age group (a and b) per balance assist activation status (On: activated, Off: deactivated) are indicated.

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

There was no significant effect of Aging or Balance assist system on steering rate (Figure 4, Table 2). However, there was an effect of Disturbances on steering rate in multi-task cycling showing higher steering rate in disturbed compared to undisturbed cycling (t = 3.590, p = 0.001).

In multi-task cycling, there was no significant effect of Aging, but there was an effect of Disturbances and Balance assist system on bicycle's roll rate (Figure 4, Table 2). There was not any interaction between these factors (Table 2). Results showed higher bicycle's roll rate in disturbed compared to undisturbed cycling (t = 4.912, p = <0.001), and when balance assist system was activated, regardless of age or disturbances, bicycle's roll rate was found to be lower than when deactivated (t = -4.419, p = <0.001).

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

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. The bold values indicate the significant effect, p<0.05.

Scenario 2; Multi-task	Steering rate		Roll rate		Lean rate	
	F	p	F	p	F	p
Balance assist	**19.531**	**<0.001**	0.952	0.339	3.231	0.086
Disturbances	**24.131**	**<0.001**	**12.888**	**0.001**	3.190	0.088
Age	0.013	0.911	0.224	0.640	0.099	0.757
Balance assist * Disturbances	2.670	0.115	2.549	0.123	3.045	0.095
Balance assist * Age	1.261	0.272	0.134	0.718	2.066	0.165
Balance assist * Disturbances * Age	0.567	0.458	0.485	0.493	0.650	0.429

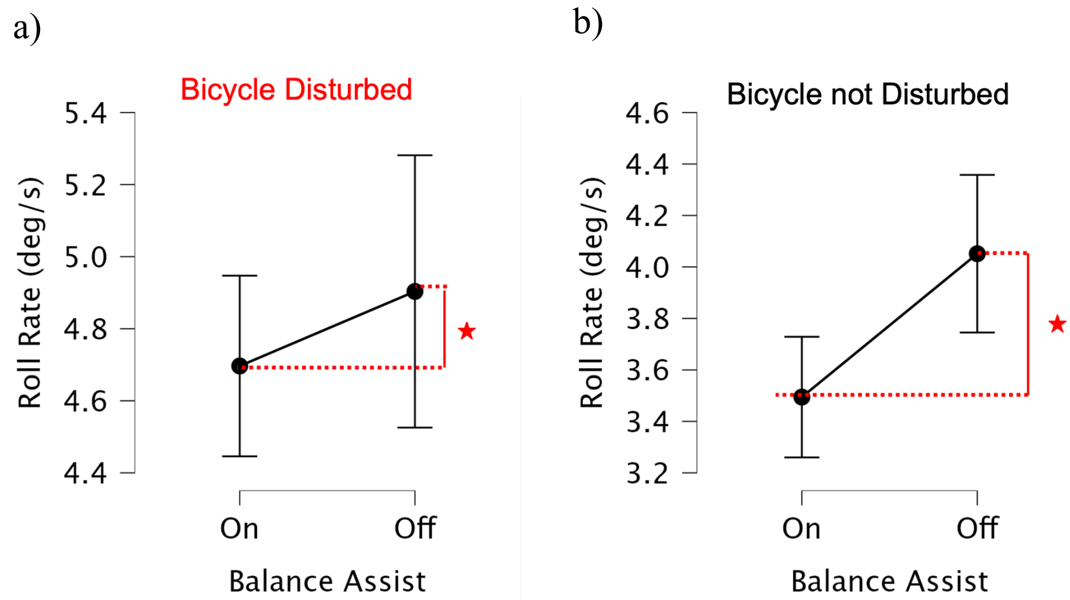

Figure 4. The effect of the Balance assist system on bicycle's roll rate a) in presence and b) in absence of disturbances among both age groups in multi-task scenario. Average and error bars with 95% confidence interval of all subjects per balance assist activation status (On: activated, Off: deactivated) are indicated.

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

Furthermore, there was no significant effect of Aging, but there was an effect of Scenario and Balance assist system on bicycle's steering rate (Table 3). There was not any effect of interactions between factors. Post-hoc showed that the steering rate in single-task is lower than in multi-task cycling ($t = -2.112$, $p = 0.044$), and when balance assist system was activated, regardless of age and scenario, the steering rate was lower than when deactivated ($t = -2.876$, $p = 0.008$).

There was no significant effect of Aging, but there was an effect of Scenario and Balance assist system, and an interaction of Balance assist system * Aging on bicycle's roll rate (Table 3, undisturbed trials). Post-hoc showed that the bicycle's roll rate in single-task is lower than in multi-task cycling ($t = -2.832$, $p = 0.008$), and when balance assist system was activated, bicycle's roll rate decreased only in older participants ($t = -6.641$, $p < 0.001$).

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

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

All undisturbed trials single vs. multi-task	Steering rate		Roll rate		Lean rate	
	F	p	F	p	F	p
Balance assist	**8.269**	**0.008**	**43.498**	**<0.001**	0.211	0.652
Scenario	**4.462**	**0.044**	**8.023**	**0.008**	0.514	0.484
Age	0.099	0.775	1.041	0.316	2.217	0.157
Balance assist * Scenario	4.962e^-4	0.982	0.018	0.894	1.114	0.308
Balance assist * Age	0.464	0.501	**7.823**	**0.009**	0.248	0.626
Balance assist *Scenario * Age	0.277	0.603	0.002	0.965	0.01	0.923

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 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 in single-task cycling the balance assist damped the lateral motion (roll rate) in all cyclists but more significantly in older cyclists compared to young ones, both in disturbed and undisturbed conditions. Regarding the steering effort, we found that the balance assist decreased the steering rate (effort) in single-task scenario in both age groups, indicating that less effort may be required to steer and balance the bicycle. The steering effort in multi-task scenario was not affected by balance assist. 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

We have found that older participants showed poorer bicycle balance control than younger participants. This was evidenced by a higher bicycle roll rate which quantifies the rider's reduced ability to control the bicycle's rolling motion. The reduced ability is expected due to degradation in older adults' balance systems. Our results showed improved bicycle balance control when balance assist system was activated in both age groups, as evidenced by reduced bicycle's roll rate. The reduced roll rate was more significant in older participants. In these cases, no significant differences were found in older and young participants' bicycle balance control (roll rate) when using balance assist system, suggesting similar bicycle balance control in both age groups. Our results might suggest that, when balance assist system is activated, the states of the bicycle are processed at bicycle's control unit earlier than they would be at older cyclists' 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. Furthermore, in all undisturbed trials, regardless of the type of scenario, a larger improvement in lateral balance control was observed in older participants. 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.

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.

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 in multi-task scenario. 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 both single- and multi-task cycling, in which only balance assist system proved to be effective to decrease the steering rate in single-task cycling. This indicates that less steering action is needed to regain balance control after being subjected to disturbances. This may 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. The findings suggest that in multi-task cycling the priority was to maintain or regain lateral balance control, regardless of the amount of the steering actions to reach that point. Since multi-tasking is not happening during the whole duration of cycling in real-life situations, the risk of fatigue due to steering action is not the main safety concern.

Balance assist and multi-tasking

In undisturbed conditions, when performing a 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, regardless of the scenarios in all undisturbed conditions. 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. In contrast to single-task, balance assist system did not improve the steering effort in multi-task scenario. Nonetheless, cyclists and especially older participants with lower physical fatigue threshold could benefit from this aspect 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. 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.

Conclusion

Our balance assist system showed to be effective in improving lateral balance by reducing the lateral motion variability not only in single-task but also in multitask cycling, and both in presence and absence of disturbances. The improved balance was more prominent for older adults in single-task cycling. The balance assist system also showed reduced steering effort indicated by reduced steering rate in single-task cycling.

In multi-task cycling, however, the presence of balance assist helped riders to have a better balance as seen in reduced lateral roll rate motion, riders made equal steering effort in keeping the bicycle balanced. Adding human motion detection and estimation to the control algorithm could further improve the effectiveness of the balance assist system.

Acknowledgement

This study is funded by Dutch Research Council, Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), under the Citius Altius Sanius program and in collaboration with Bosch eBike Systems and Royal Dutch Gazelle. Authors would like to thank the individuals who participated in the experiment. Authors would also like to thank Arend Schwab, and their collaborators at Bosch eBike Systems and Royal Dutch Gazelle for their contribution to developing the balance assist system.

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Appendix 1

Since motion variability is expected between rides at 1 m/s and at 5 m/s with the same rider, we performed Post Hoc ANOVA analysis to confirm the subjects followed the instruction and kept the speed constant. The analysis confirmed the constant speed assumption as we found that there were no significant differences in average, standard deviation, and range of speed (maximum-minimum speed) between trials per subject ($F= 0.296$, $p = 0.828$; $F= 0.444$, $p = 0.721$; $F= 1.146$, $p = 0.226$, respectively).

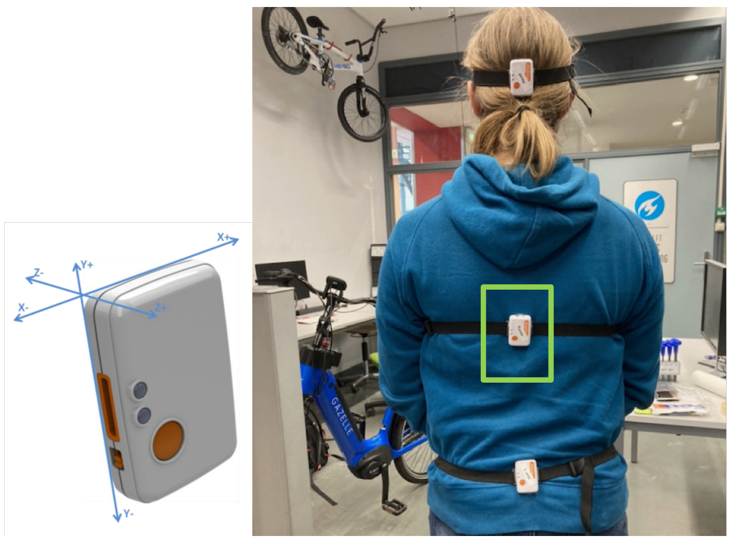


Figure S1. Shimmer3 IMU (3 axis) sensors placement on one young participant. The data from the torso was used in the analysis.

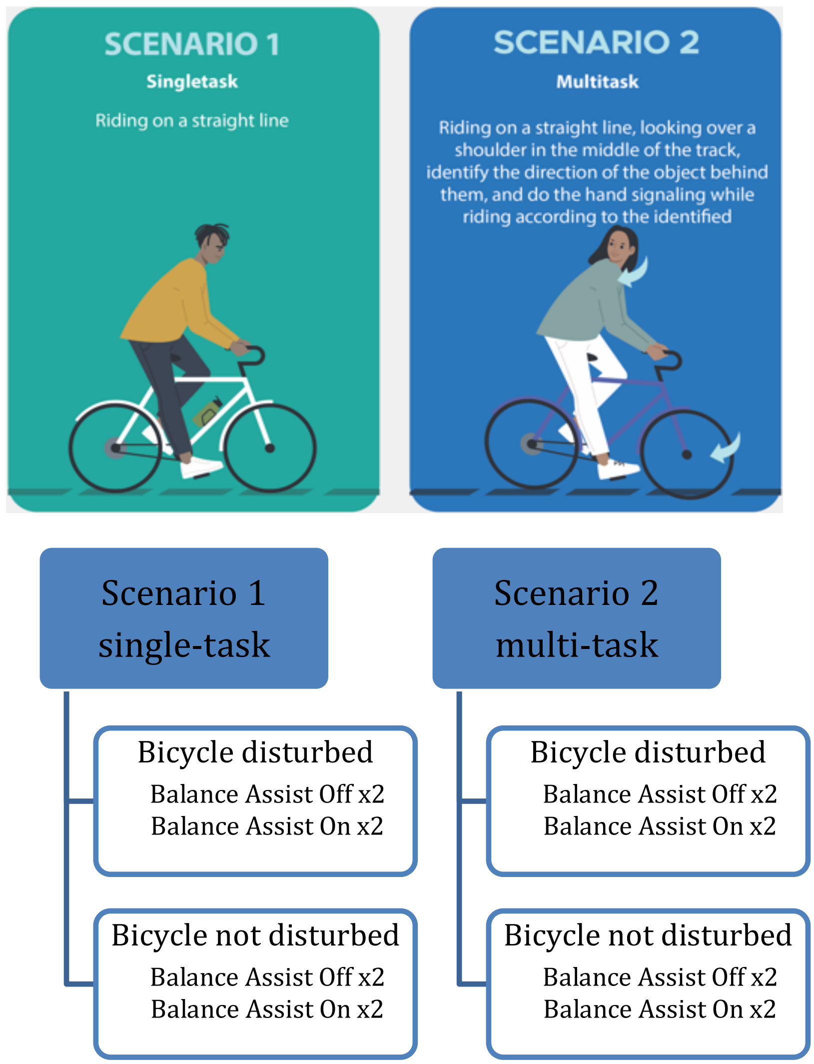


Figure S2: Experimental procedure shows in total sixteen trials in two scenarios, four conditions per scenario with repetition; both scenarios were performed with and without the balance assist system. First scenario, single-task in presence and absence of disturbances (0.5 s), and second scenario, multi-task with shoulder check in presence and absence of long disturbances (1 s).

a)

b)

c)

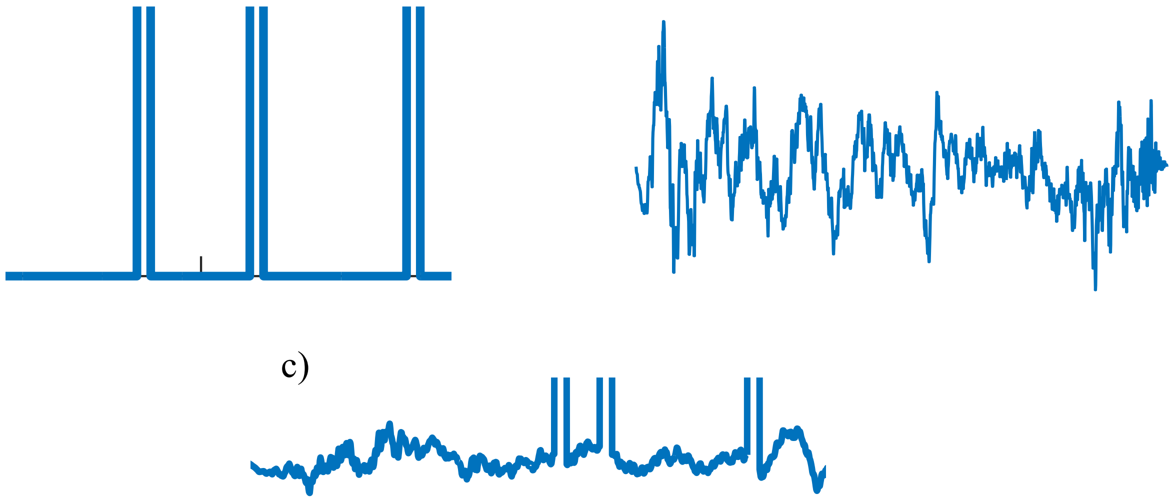


Figure S3. Demonstration of the implementation of timeseries data of a) disturbance induced torque, b) balance assistive torque, and c) disturbance and the balance assistive torque.

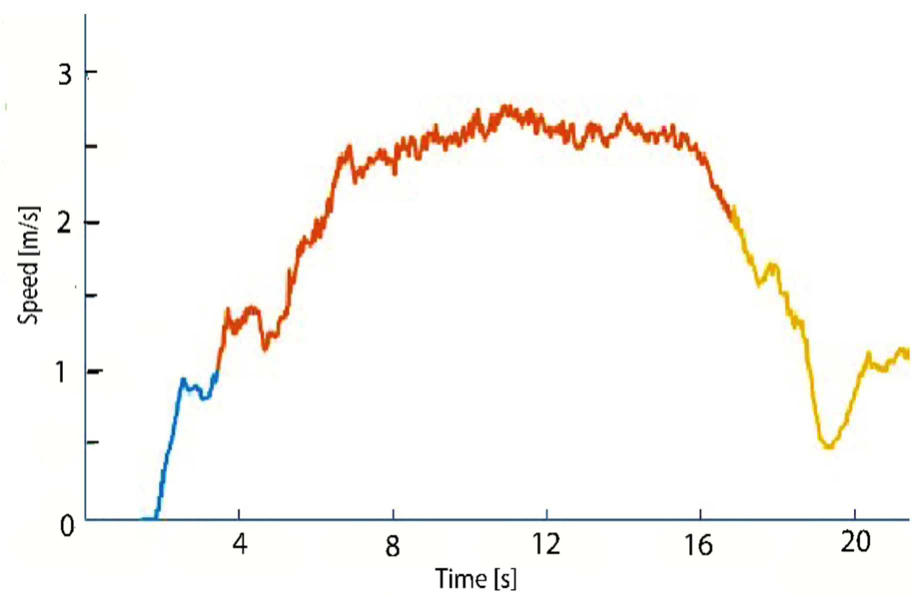
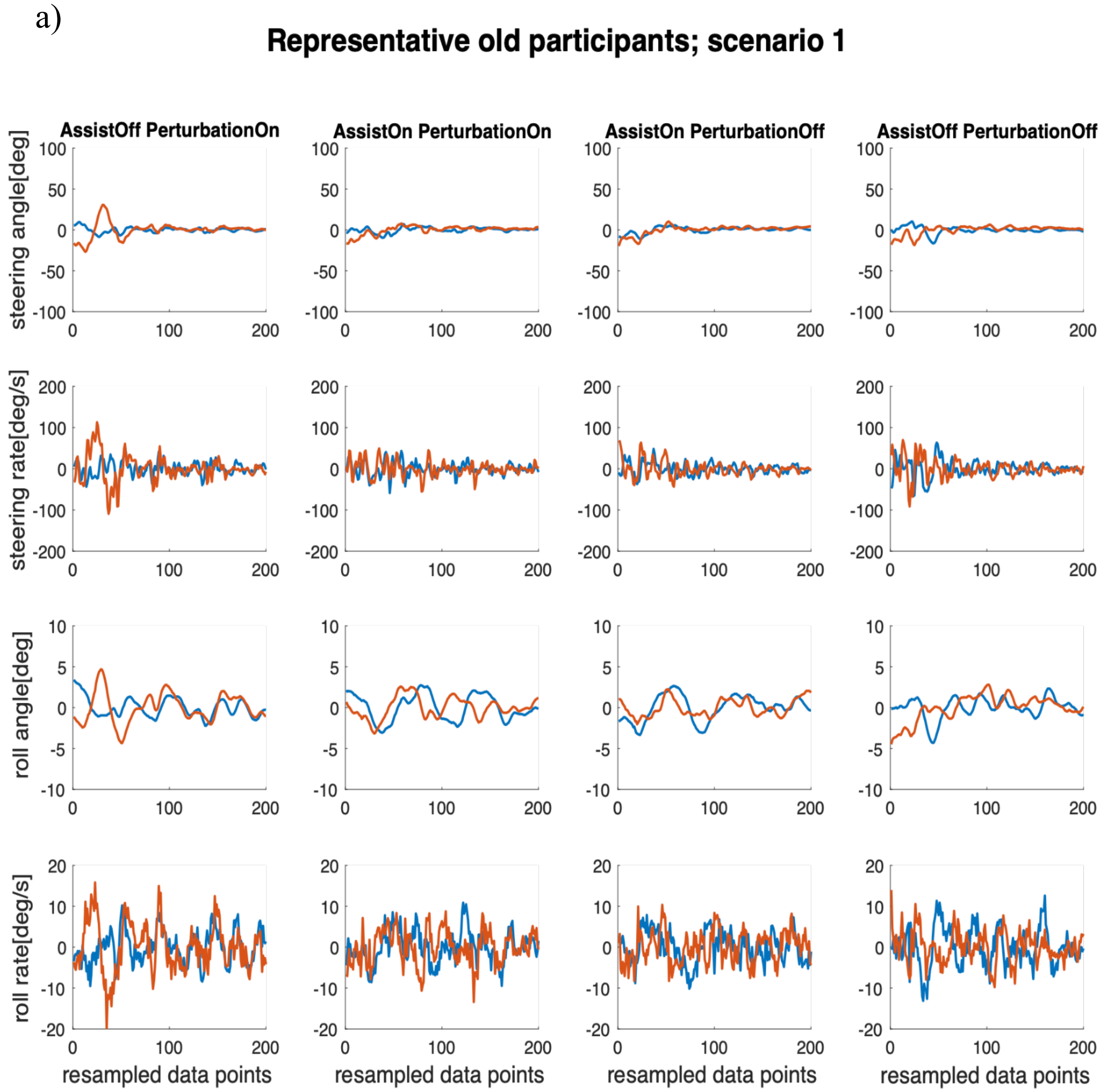


Figure S4. The red line shows the segmented part of the time series starting at 1 m/s forward speed. The end is where the distance from the starting point reaches 30 m.

a)



Representative old participants; scenario 1
AssistOff PerturbationOn
AssistOn PerturbationOn
AssistOn PerturbationOff
AssistOff PerturbationOff
steering angle[deg]
steering rate[deg/s]
roll angle[deg]
roll rate[deg/s]
resampled data points
resampled data points
resampled data points
resampled data points

b)

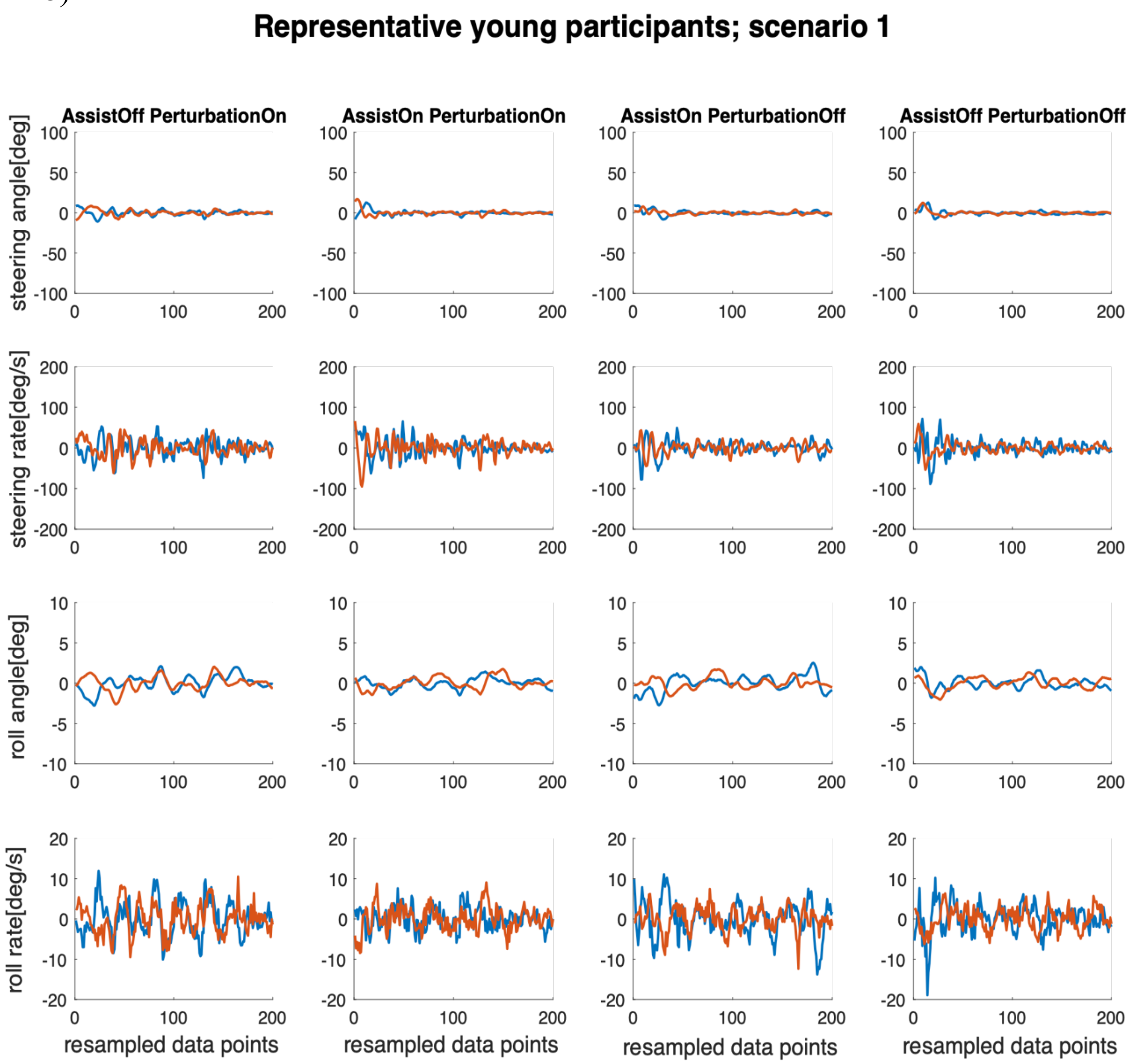


Figure S5. The resampled steering and roll angle and rate for a) one representative old (top panel) and b) one representative young participant (bottom panel) performing the single-task cycling scenario. 8 trials consisting of four conditions with a repetition (balance assist on/off (2) * bicycle disturbed/not disturbed (2) * repetition (2)) are shown. The red and blue lines represent two repetitions per condition. X axis represents the data points after resampling.

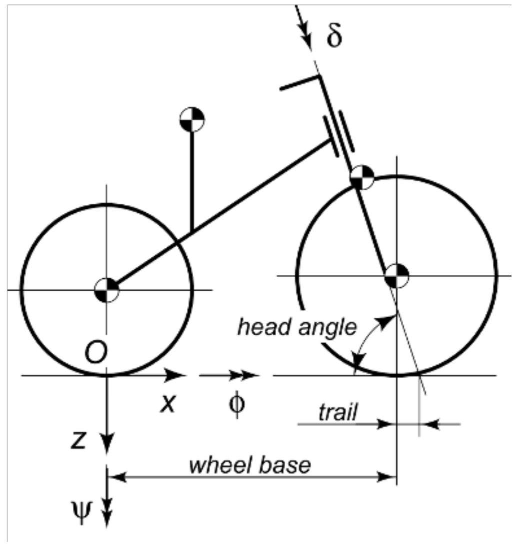


Figure S6. roll angle around the X or forward axis, and steering angle around the steer axis δ (Schwab et al. 2005)

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Schwab AL, Meijaard JP, Papadopoulos JM. 2005. Benchmark results on the linearized equations of motion of an uncontrolled bicycle. J Mech Sci Technol. 19(1 SPEC. ISS.):292–304. https://doi.org/10.1007/bf02916147