Supplementary Online Material

for

A Model Based on Cyclist Fall Experiments which Predicts the Maximum Allowable Handlebar Disturbance from which a Cyclist Can Recover Balance

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Summary

This Supplementary Online Material (SOM) presents the experimental data and detailed information on the statistical analyses conducted, as well as recommendations for future research directions that extend beyond the scope of the main paper. Additionally, it includes several aspects of our study with practical applications that go beyond the modeling emphasis of the main paper. Together, these elaborations are intended to encourage further research in the field.

Contents

Chapter 1

Experimental data & statistical analysis.

The experimental data and the R-script used for the statistical analysis are hosted on github at: https://github.com/fmeulen/CyclingFall

- The csv file 'PerturbedCyclistExperimentalDataTUDelft2022.csv' contains the experimental data used in the statistical data analysis can be found at:
  https://github.com/fmeulen/CyclingFall/blob/main/PerturbedCyclistExperimentalDataTUDelft2022.csv
- The script 'cycling_fall_figs_for_article.R' produces the analyzes and figures within the article, and can be found at:
  https://github.com/fmeulen/CyclingFall/blob/main/cycling_fall_figs_for_article.R
- The script 'cycling_fall_full_analysis.Rmd' is an R-markdown file that does the full statistical analysis, but also contains extra exploratory figures and fitted models, and can be found at:
  https://github.com/fmeulen/CyclingFall/blob/main/cycling_fall_full_analysis.Rmd
  When run, it produces the html file 'cycling_fall_full_analysis.Rmd.html', which also can be found at:
  https://github.com/fmeulen/CyclingFall/blob/main/cycling_fall_full_analysis.html

Chapter 2

Details on protocol and setup of the experiments

Participants were informed of the research procedures before they gave informed consent according to the guidelines of the Delft University of Technology human research ethics committee. All participants participated voluntarily.

Below, we describe the protocols to let the participant gain trust that the harness would catch him or her when falling and learn how to cycle on the treadmill — followed by a description of the protocol used to determine the MAHD per participant.

2.1 Protocols to gain trust in the harness and learn how to cycle on the treadmill

The protocol to gain trust in the harness started without the bicycle. The participants were instructed to stand on the treadmill away from the bicycle while wearing the harness, with a spotter beside them. They could first let themselves fall sideways and make a sidestep if they felt the harness would not catch them on time. The spotter would also intervene to catch the participant if he or she thought the participant would fall. This procedure was repeated until the participants indicated they felt safe, usually two to three times. The spotter did not have to intervene a single time. Next, the participants were instructed to sit on a standing-still bicycle, still wearing the harness, and hold on to a fence on the right-hand side, which was also covered in padding and could fold away during the experiments. The participants were then instructed to let go of the fence and let themselves fall to the left. Participants could use their left feet to catch them if they thought they would fall and the harness would not catch them. This was repeated until the participants indicated that they felt safe. Usually, this was three to four times.

Finally, the participants were allowed to perform a self-intended fall while cycling without a disturbance. Approximately a third of the participants chose this option. Before a participant could do this, he or she needed to learn to cycle on the treadmill.

Participants needed to learn to cycle on the treadmill because although the dynamics of cycling straight ahead with constant forward speed is the same for cycling on a treadmill compared to cycling outside, the sensorial input, such as optical flow, is different for the cyclist. The participants learned to cycle on the treadmill at moderate speed. Participants could hold on to a fence, covered in padding, on the right-hand side for balance while the treadmill got up to the prescribed speed. Once the participants felt the treadmill had sufficient speed (an operator also communicated the current speed of the treadmill), they could let go of the fence. Another operator would then remotely fold the fence by pulling a rope that would unlock the support of the fence. The foldable fence was also used during the experiments. Participants could hold on to it every time the treadmill was started. The fence was always folded when the steer torque disturbances were applied.

The learning phase was finished if the participant could cycle in a controlled way for several seconds 10 cm from the left and right border of the treadmill and one minute on the centerline of the treadmill. Most participants needed between one to five attempts before they could cycle steadily and straight ahead at the constant prescribed speed of the treadmill. For most participants, this took approximately ten minutes. One participant took almost an hour to complete the learning phase.

Once the participants had learned to cycle on the treadmill, they were given a feel for the handlebar torque disturbances while standing still, holding the handlebars, wearing the harness, and standing with two feet on the ground. The participant was then given two or three low steer torque disturbances. After this, the experiments started.

2.2 Protocol to determine the MAHD

It is highly unlikely that there will be a clear-cut boundary between falling and being able to recover (i.e. the MAHD) for any participant. More likely, due to human variations in response to a disturbance, there is a probability that a participant will fall depending on the magnitude of the disturbance. To determine the MAHD for a participant, we applied several disturbances varying in magnitude so that the participant both fell and recovered balance multiple times. Using a logistic regression model, we can then convert a binary outcome (i.e. fall or recovery) into a probability as a function of the disturbance magnitude.

To illustrate this concept, Figure 2.1 displays the outcomes of a simple logistic regression analysis applied to the example trial data from Figure 2.2. In the rest of this study, we define the MAHD as the threshold at which there is a 50% probability the cyclist will fall. In section **??**, we describe the Bayesian multilevel logistic regression model used to determine the MAHD for each participant.

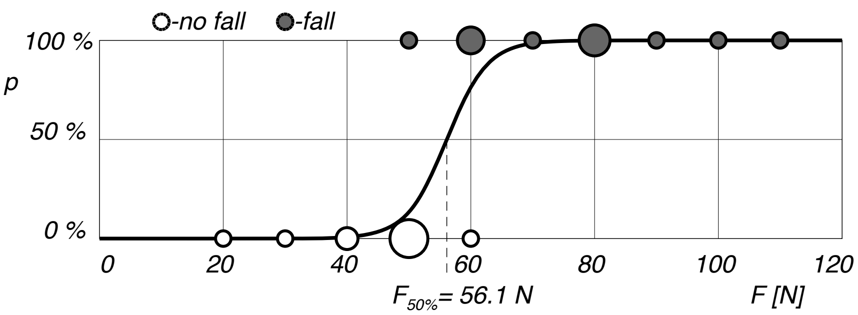

Figure 2.1: Example of a logistic regression model applied to the pull force data from figure 2.2. The white dots mark no fall, the dark dots mark a fall, and the area of the dots corresponds to the number of pulls at that specific force value. The solid line is the logistic regression line for the probability p of falling as a function of the pull force F. The pull force for which there is a 50 % chance of falling is $F_{50\%} = 56.1$ N. This corresponds to an angular impulse of 13 Nms.

To start with a reasonable guess of the MAHD, we performed a simple staircase search procedure, during which the magnitude of the disturbances was increased by a constant step size if the preceding disturbance did not result in a fall. This procedure stopped once the participant fell. The magnitude of the last disturbance was then chosen as the initial estimate of the MAHD for the experiments. These initial disturbances started with forces of 20 N (equivalent to handlebar

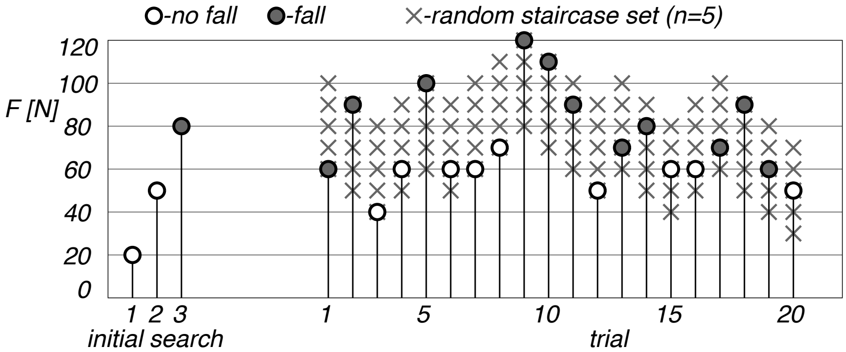

Figure 2.2: Example of the random and adaptive staircase procedure to find the MAHD of the pull force F applied at the handlebar for which a cyclist will not fall. White dots mark no fall, dark dots mark a fall, and grey crosses show potential pull forces from which is chosen at random. The initial search is to locate where the random staircase procedure should start.

torques of 9 Nms) and increased with steps of 30 N (equivalent to 6 Nms). Most participants fell after two or three disturbances, and only one had already fallen at the first.

The disturbance forces during the experiment were chosen according to a random and adaptive staircase procedure, enabling disturbance forces to be performed above and below the falling threshold and to allow small progression of the threshold (Doll et al. 2014). The random staircase procedure works as follows. A set of five equidistant disturbance forces centred around the initial estimate MAHD was defined, from which the upcoming force was randomly selected. All five forces were 10 N apart and were increased or decreased with a fixed step size of 10 N after a balance recovery or fall, respectively. The step size was chosen after several pilot tests and is a trade-off between accuracy and the required time to determine the MAHD. Clockwise and counter-clockwise disturbances were presented in random order. If the random staircase algorithm proposed a zero or negative disturbance force, the outcome was assumed to be no fall, and the operator continued to the next disturbance. An illustration of the simple and random staircase procedure (with twenty disturbances) is given in Figure 2.2.

The participants were told before the experiment started that a handlebar disturbance would be applied and were instructed to brace themselves and try their best to recover balance. After a recovery, participants were to return to the centerline of the treadmill, after which a new disturbance was presented. In case of a fall, participants were caught by an intelligent tethered harness, and the treadmill was stopped with the emergency stop button. The participant was helped upright again and placed back upright in the middle of the treadmill. After this, the treadmill was started again, and once the participant cycled steadily again, a new disturbance was applied.

Each participant started the experiment at a prescribed cycling speed of 12 km/h. After the first fall (the initial guess), a maximum of twenty disturbances were applied to each participant at each forward speed. This number is a trade-off between the four hours available per participant, the physical effort it costs participants, and the minimum number of trials required to obtain a robust and reliable estimate of the disturbance threshold. Only one participant stopped after ten disturbances; all others completed all twenty disturbances.

During this set of twenty disturbances, participants could stop or take a break at any time they wished. Several participants took one break of five to ten minutes in a set of twenty disturbances. Several times, there was also a break because of small reparations to the set-up. For a small number of disturbances, the operator stopped the treadmill too soon before it was certain the participant would have fallen, or the perturbator mechanism did not apply the disturbance correctly. In this case, the same disturbance was applied again, and data from the previous disturbance was discarded.

After a participant finished a set of twenty disturbances, there was a break in which he or she was given the choice to redo the experiment at another velocity. If the participant agreed to this, it was randomly selected if the velocity was 6 or 18 km/h. After the participants finished the set of twenty disturbances at this velocity, they were given the choice to redo the experiment at the last remaining velocity.

The three speeds were chosen based on the results of several pilot studies. In pilot studies, participants indicated that 12 km/h was a comfortable speed. Participants further indicated that 6 km/h was the slowest speed at which they could still cycle steadily and straight ahead, and 18 km/h was the maximum speed limit of the treadmill. During the experiments, several participants spontaneously noted that a treadmill speed of 12 km/h felt subjectively comparable to 18 km/h on an open road and a treadmill speed of 18 km/h felt much faster than 18 km/h on an open road.

If the participant agreed to perform the experiments at another velocity, the procedure to learn to cycle on the treadmill at that speed and the simple staircase procedure to determine an initial estimate for the MAHD were repeated at that velocity.

2.3 Details on the experimental setup

Details on the experimental setup and the processing of the raw experimental data from the motion capture system can be found in the 2020, Delft University of Technology, MSc thesis, by Shannon van de Velde[1]. A copy of the thesis can be found at the TUDelft repository at:
https://resolver.tudelft.nl/uuid:4571c00e-3bfc-4d9c-a46a-30a3b30b932a

[1] S. van de Velde, Design of a setup for experimental research on stability of a bicycle-rider system subject to large perturbations, 2020, MSc thesis, Delft University of Technolgy

Chapter 3

Practical applications of the cyclist fall model

Presented here are several aspects of our study with practical implications that go beyond the modeling emphasis of the main paper.

3.1 Prioritisation of which disturbances to eliminate

The Bayesian multilevel logistic regression model we developed to predict the MAHD for cyclists with different characteristics can serve as a valuable tool in determining which disturbances can be considered safe (i.e. below the MAHD). This model provides valuable insights into which disturbances are safe (i.e., below the MAHD) and which are not, guiding decisions on allowable disturbances in cycling environments. For example, if a cyclist can maintain balance after a perpendicular collision with a car travelling at 30 km/h (of this is below the MAHD) but not at 50 km/h (if this is above the MAHD), it is advisable to limit the maximum speed at car-bicycle intersections to 30 km/h. Another scenario involves collisions with curbs. Different curb designs — such as high vertical curbs, low vertical curbs, or sloped curbs — generate varying impact forces, potentially resulting in disturbances of different magnitudes. Identifying which designs produce disturbances below the MAHD will inform safer curb implementations. However, before real-world disturbances can be compared to the MAHD, they must be accurately measured and translated into equivalent handlebar disturbances.

3.2 Develop disturbance-based cyclist skill training programs

Our findings underscored considerable variability in fall risk among cyclists, with individual cycling skills emerging as the primary predictor of falls, outweighing factors such as age, mass, length, reaction time, and control effort. This finding suggests that investing in cycling skill training could mitigate fall risks effectively. This finding holds for all cyclists, not only older cyclists. As demonstrated in our experimental setup, implementing disturbance-based training holds promise for enhancing cyclists' ability to recover balance from significant disturbances, as our results showed that later disturbances tended to increase the MAHD. However, the generalizability of this training to different disturbances and real-world cycling contexts warrants further investigation.

3.3 Increased (emergency) lateral space to recover blance

Additionally, our results indicate that providing increased lateral space for balance recovery can lower the probability of falls, advocating for increased emergency lateral space for cyclists. While widening bicycle paths can contribute to this goal, alternative solutions such as forgiving curbs or rideable road shoulders might also be effective.

3.4 Experimentally evaluate cyclist fall prevention interventions

The experimental platform, combined with the MAHD, can already be used to test the effectiveness of cycling safety interventions before they are implemented. For example, it can be used to test different bicycle designs or the medical fitness needed to cycle safely. With this approach, we do not have to wait until bicycle dynamics and cyclist control models have been validated and improved.

3.5 Screen cyclists for fall risk

Finally, the Bayesian model, combined with the experimental setup, can be used to screen individual cyclists' fall risk and serve as a disturbance-based training program. The experimental setup can be used to screen individual cyclists for fall risk (i.e. low MAHD). Because age was not an important predictor for the MAHD, older cyclists do not necessarily have a higher fall risk. A screening would allow for the identification of individuals with a high fall risk. Consequently, personalised advice regarding the risks of cycling could be provided. Such advice might consist of potential steps to mitigate these risks. For instance, advice to wear a bicycle helmet, transition to a tricycle, or undergo training to improve cycling balancing skills.

Chapter 4

Recommendations for future research

Presented here are recommendations for future research directions that extend beyond the scope of the main paper.

4.1 Investigate the impact of the participant's awareness and heightened focus on the MAHD

Understanding how participants perceive and respond to disturbances during balance or movement tasks is critical for interpreting the results of our study. In particular, the degree to which participants are aware of upcoming disturbances may influence their anticipatory responses. Future research should systematically investigate how participants' awareness and heightened focus on impending disturbances influence the MAHD.

Exploring the aspect of unpredictability within the experimental setup, although challenging, is feasible to some extent. With a refined understanding of the safety aspects of the experimental setup, future investigations could disturb participants without prior notification, removing their awareness of impending disturbances. However, it is important to note that this opportunity is limited to the first instance, as subsequent disturbances are likely to be anticipated. Given the necessity for multiple disturbances to determine MAHD accurately, relying on a single disturbance would require a considerably large and labour-intensive sample size and many inter-subject comparisons.

An alternative approach involves introducing a dual task for participants, which could divert their focus from the impending disturbances, resembling real-life conditions where distractions increase the risk of falls. Conducting experiments with a dual task is valuable, considering distraction as a recognised risk factor for cycling crashes. However, caution is warranted in designing and executing such experiments, as individuals allocate attention and cognitive resources differently between the two tasks, potentially impacting performance and confounding the results of the MAHD.

4.2 Obtain force and torque profiles of real-world disturbances

At present, there is a lack of systematically collected data on the force and torque profiles of real-word disturbances, limiting our ability to directly relate the obtained values for the MAHD to real-world disturbances. We recommend that future research focus on gathering these profiles. These profiles could be collected by equipping bicycles with accelerometers or gyroscopes to collect data during events such as riding over potholes, colliding with curbs, encountering sudden wind gusts, or collisions with other road users. By measuring the resulting steering rates from these disturbances and cataloguing the data, it would be possible to establish a correlation between real-world disturbances and the MAHD.

4.3 Investigate strategies to recover balance from large disturbances

Another important aspect for future research is further investigating strategies to recover balance from large disturbances in conditions with limited lateral space. While there is one single response to recover balance from a disturbance, which is to steer in the direction of the fall, it is sometimes important to postpone balance recovery so as not to ride off the side of the road. Cyclists might use different strategies, or prioritisation, to recover balance quickly and not get too close to the side of the road. This prioritisation is not captured by existing cyclist control models, based on experiments in which cyclists were subjected to only small disturbances, as the lateral space in these conditions is often not a constraint.

While steering into the direction of the fall was observed as the primary balance recovery mechanism across all participants, variations in strategies may still arise due to the limited width of the treadmill. These subtle strategy differences may be discernible by analysing steering reactions captured during cyclist fall experiments. However, studying such patterns and strategies was outside the scope of this study.

Another potential strategy difference lies in how cyclists prepare for disturbances. Participants may stiffen their arm muscles to minimise or resist handlebar disturbances, theoretically facilitating easier balance recovery. Although we attempted to gather information about muscle stiffening and reaction time through EMG signals from the biceps and triceps, data processing challenges posed by signal noise led us to exclude this variable from the cyclist fall experiments and our study's scope.