Supplementary Material

Additional Recommendations for Future Research and Practical Applications

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Overview

This supplementary document provides additional recommendations for future research directions that extend beyond the scope of the main manuscript. Additionally, several other elements of our study have practical implications beyond the modeling focus which was the focus of the main script. These can also be found in this supplementary document. Bot these elaborations are intended to inspire more investigations in the field.

1 Recommendation 1: investigate the impact of the participant's awareness and heightened focus on the MAHD

Investigating how participants' awareness and heightened focus on impending disturbances influence the MAHD is essential for a comprehensive understanding of the results. 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.

While these approaches may reduce participants' awareness of upcoming disturbances, they will likely remain more alert and aware than in real-world situations due to the experimental setup and safety harness. Comparisons of cyclist steer actions from naturalistic studies can shed light on these differences. However, one must conclude that complete environmental validation is practically impossible.

Lastly, all participants were experienced cyclists with years of weekly cycling experience. Therefore, the applicability of our experimental approach to inexperienced cyclists is yet uncertain, as they may struggle more with treadmill cycling. Nevertheless, despite the participants' experience, significant variance was already observed among them, which will be discussed further in the subsequent section on key cyclist characteristics predictive of fall outcomes.

2 Recommendation 2: obtain force and torque profiles of real-world disturbances

Unfortunately, the obtained values for the MAHD cannot be directly linked to real-world disturbances, as force and torque profiles of such disturbances have yet to be systematically collected. 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.

3 Recommendation 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.

These unidentified cyclist variables influencing the MAHD may relate to the strategies employed by cyclists to recover balance after a disturbance, an aspect not considered in our study. 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. The finite width of the treadmill imposes constraints on lateral displacement before a fall occurs. Consequently, cyclists face a trade-off between quickly recovering balance by steering towards the fall direction and staying within the treadmill's lateral width by delaying recovery and steering in the opposite direction. Cyclists may adopt different strategies, prioritising swift balance recovery or staying further from the treadmill belt's side edge. 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.

4 Practical application 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.

5 Practical application 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.

6 Practical application 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.

7 Practical application 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.

8 Practical application 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.