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Research article

The maximum allowable handlebar disturbance: An indicator for the ex-ante evaluation of cycling fall prevention interventions

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Falls due to disturbances are a common cause of serious cycling injuries, yet evaluation approaches to systematically evaluate interventions aimed at improving balance recovery are lacking. Current ex-post evaluations are hindered by sparse crash data, and existing ex-ante approaches often lack generalizability or rely on surrogate measures that are not validated against fall risk. This study introduces the *Maximum Allowable Handlebar Disturbance* (MAHD), a novel performance indicator that quantifies the largest handlebar disturbance a cyclist can recover from without falling. The MAHD captures the cyclist's resilience to disturbances and provides a direct, interpretable measure of intervention effectiveness. We propose two methods for determining MAHD: (1) controlled treadmill experiments with induced handlebar disturbances and safe fall conditions and (2) simulations using bicycle dynamics and cyclist control models. Together, these methods allow quantitative ex-ante evaluation and systematic comparison of interventions targeting cyclist control, bicycle design, and infrastructure features such as curbs and road shoulders. With further validation, the MAHD offers practical value for researchers, engineers, and policymakers seeking to design safer bicycles, training programs, and road environments and improve evidence-based resource allocation. In the future, this could reduce fall-related cycling injuries.

1. Introduction

Cyclists account for a growing share of serious traffic injuries in the European Union, increasing from 15% in 2011 to 24% in 2020 (Commission, 2023). This trend poses a challenge to achieving global road safety goals, including Sustainable Development Goal 3.6, which aims to halve traffic injuries. To reverse this development, it is essential to target common crash types with evidence-based interventions (World Health Organization, 2023).

A frequent cause of injury among cyclists is a fall resulting from a disturbance that throws the cyclist or bicycle off balance (Utriainen et al., 2023). Cycling requires continuous balance (Kooijman et al., 2011). Even minor disturbances—such as uneven surfaces, sudden shifts in body weight, or unintended steering inputs—can lead to a loss of balance and a fall. While most cyclists recover from small disturbances, recovery may fail when disturbances are large or when the cyclist's reaction is insufficient. Falls resulting from such disturbances have been consistently identified in accident studies (Utriainen et al., 2023), indicating their prevalence.

Three broad strategies exist to reduce such crashes. The first is to eliminate disturbances from the cycling environment through measures such as protected bike lanes and speed management. These interventions have been widely implemented and positively

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evaluated in ex-post studies (Thomas & DeRobertis, 2013; Elvik, 2001). The second strategy is to mitigate the consequences of falls, for instance, through protective equipment like helmets or airbags (Hoye, 2018). Both strategies are important, and their effectiveness is relatively well understood. In contrast, much less is known about a third strategy: enhancing the cyclist's or bicycle's ability to recover balance once a disturbance occurs. This study therefore focuses on this third strategy. Interventions in this category include (balance) training programs (Keppner et al., 2023), bicycle design innovations such as balance-assist technologies (Alizadehsaravi & Moore, 2023), and infrastructure modifications like rideable shoulders or sloped curbs (Westerhuis et al., 2020). These aim to improve the likelihood of balance recovery following a disturbance.

However, evaluating the effectiveness of such interventions remains a challenge. Ex-post evaluation is hindered by the lack of appropriate data for reliable statistical analysis—either because the interventions have not been implemented at scale or because relevant variables are not systematically recorded in national bicycle crash databases. Ex-ante evaluations are typically intervention-specific and lack generalizability (Keppner et al., 2023; Alizadehsaravi & Moore, 2023). Moreover, the commonly used experiments and performance indicators—such as changes in lean angle or changes in errors under normal cycling conditions—are indirect measures of fall risk and have not been validated against actual fall events.

This gap limits the ability of designers and policymakers to make informed, evidence-based decisions during the design phase of these types of interventions. As a result, potentially effective solutions may be overlooked or ineffective ones implemented.

The goal of this study is to improve the ex-ante evaluation of interventions that improve balance recovery. We propose a novel quantitative performance indicator: the Maximum Allowable Handlebar Disturbance (MAHD). This metric reflects the cyclist's ability to recover balance following a disturbance. We demonstrate how the MAHD can be determined using laboratory experiments or through bicycle dynamics and cyclist control models and how it can be used to to evaluate and compare balance recovery interventions systematically.

The MAHD represents a first conceptual framework for disturbance-based evaluation of interventions targeting cycling balance recovery. As with other disturbance-based performance indicators in human movement science, its practical implementation is expected to evolve through empirical validation and refinement.

2. Methodological Framework/Methods

This section presents the proposed performance indicator for the ex-ante evaluation of cycling balance recovery interventions and the two approaches to determine it: through controlled experiments and through simulations using bicycle dynamics and cyclist control models.

2.1 Definition of the Maximum Allowable Handlebar Disturbance

We propose the *Maximum Allowable Handlebar Disturbance* (MAHD) as a novel quantitative performance indicator to evaluate cycling balance recovery interventions. The MAHD quantifies the upper threshold for an impulse-like external handlebar disturbance beyond which a cyclist can no longer recover balance. It reflects the resilience of the cyclist–bicycle system in response to sudden disturbances. Interventions that increase a cyclist's MAHD are considered effective in improving balance recovery.

The MAHD is defined as an applied external torque impulse about the steering axis, generated by a constant torque applied for 0.3 seconds. A clockwise torque is considered positive.

2.2 Determine the MAHD using experiments

The MAHD can be empirically determined using controlled laboratory experiments in which participants are exposed to varying magnitudes of handlebar torque disturbances. To capture actual falls while ensuring participant safety, we propose these experiments are conducted on a stationary treadmill while participants are secured by a harness system Schwab et al. (2013). This setup allows for natural cycling motion within a confined area and prevents injury in the event of a fall.

Disturbances can be applied using a system of motor-controlled cables (Tan et al., 2020), which are attached to an extended handlebar. A clockwise torque can then be generated by pulling the front-left rope and rear-right rope simultaneously. A fall can be operationally defined as the cyclist leaning into the harness for support or riding off the treadmill platform.

Because human responses to disturbances vary, the boundary between recovery and fall is probabilistic. We therefore propose that each participant undergoes multiple trials with varying disturbance magnitudes. Using a logistic regression model, we can then convert the binary outcomes (i.e., fall or recovery) into a probability as a function of the disturbance magnitude. We propose that the MAHD is then defined as the disturbance level corresponding to a 50% fall probability.

To efficiently sample relevant disturbance levels near the fall threshold, a random adaptive staircase procedure can be used (Doll et al., 2014). This method allows forces to be applied both above and below the participant's estimated threshold and adjusts dynamically based on performance.

In contrast to the model-based approach, the experimental approach to estimate the MAHD does not require threshold definitions. A fall is directly observable in the experimental setup. This makes the experimental estimation substantially less sensitive to parameter choices. Recent experimental work using this proposed treadmill protocol has demonstrated that the MAHD can be reliably measured, showing clear and unambiguous distinctions between recovery and fall outcomes (Reijne et al., 2025). In practice, the randomized staircase procedure typically converges to a MAHD estimate within approximately 20 disturbances per participant at a given forward speed, allowing a full assessment to be completed in under two hours. These data also provide a first empirical foundation for calibrating and validating model-based MAHD estimates.

2.3 Determine MAHD using bicycle dynamics and cyclist control models

The MAHD can also be estimated using bicycle dynamics and cyclist control models. In this approach, the bicycle is represented by a dynamic model grounded in Newtonian mechanics. A commonly used representation is the linearized Carvallo-Whipple model, which accurately captures the motion of the bicycle for small deviations from upright cycling (Meijaard et al., 2007). Realistic cyclist's control behavior can be modeled using a nested multi-loop feedback system based on control theory, where steering inputs are generated in response to deviations in lean angle, heading, and lateral position (Moore, 2012; Schwab & Meijaard, 2013).

The MAHD can be determined using these models by performing a transient analysis in which a disturbance torque, defined as a step input lasting 0.3 seconds (as per the MAHD definition), is applied to the handlebar. The system's response is simulated for a specified duration, for example, three seconds, to observe whether balance can be recovered. The outcome is evaluated based on key bicycle state variables: lean angle φ, steering angle δ, and lateral displacement of the front wheel contact point y_Q.

Three fall modes are defined:

1. Excessive lean angle indicating lateral instability,
2. Excessive steering angle indicating overcorrection or front-end loss of control,

3. Exceeding the lateral displacement boundary, simulating the cyclist riding off the available space (e.g., edge of the road).

We propose threshold-based criteria to identify falls. Based on prior literature and engineering heuristics, we propose a critical lean angle and steering angle of 45°. Lateral displacement is limited to ±0.6 m, representing a typical buffer zone between the cyclist and the edge of a bicycle path (Schepers et al., 2023). If any of these thresholds are exceeded during the simulation, the trial is considered a fall.

It is important to emphasize that these thresholds apply exclusively to the model-based estimation of MAHD. In the experimental determination of MAHD, falls are observed directly (either by leaning into the harness for support or by leaving the treadmill platform) and therefore do not rely on predefined fall criteria. In addition, the thresholds in the model-based approach serve solely as operational definitions to allow consistent classification of fall outcomes across simulations. This distinction minimizes conceptual dependence on threshold selection and allows experimental data to serve as a benchmark for calibrating and validating model-based estimates.

If the combined bicycle and control model is linear, the MAHD can be computed analytically after an initial guess for the magnitude of the disturbance, using linear inter-polation between disturbance magnitudes that lead to fall versus recovery. If the model is nonlinear, an optimization algorithm can be used to estimate the MAHD numerically.

3. Discussion

This study proposed a novel ex-ante evaluation approach for cycling balance recovery interventions using the Maximum Allowable Handlebar Disturbance (MAHD) as a quantitative performance indicator. We presented two methods to determine the MAHD: controlled treadmill experiments and simulations based on bicycle dynamics and cyclist control models.

3.1 Disturbance-Based Indicators

The rationale for using disturbance-based indicators is supported by previous research in gait analysis, where external disturbances are used to predict fall risk and evaluate intervention effectiveness (Bruijn et al., 2013; Pijnappels et al., 2008). Since cycling requires continuous balance control as well and loss of balance is often triggered by external disturbances (Utriainen et al., 2023), it is plausible that this approach can also be successfully applied to cycling.

The MAHD is particularly suited to evaluating interventions that aim to improve balance recovery following a disturbance. This includes training programs, balance-assist technologies, and infrastructure features such as curb geometry. However, it does not generalize to all crash types, such as those caused by hard braking or dismounting events (Utriainen et al., 2023).

3.2 Choice of Handlebar Disturbance

While previous studies have applied disturbances to the rear frame via lateral pushes or shifts in tire–ground contact points (Schwab et al., 2013; Bulsink et al., 2016; Dialynas et al., 2023), this study proposes an impulse-like torque applied directly to the handlebars.

This decision was based on three main considerations.

First, the handlebars are the most sensitive part of the bicycle for balance control. Small torques at the handlebars can quickly affect the lateral motion of the bicycle and induce a loss of balance. Compared to rear-frame disturbances, handlebar disturbances require significantly less force to provoke falls, which reduces demands on the hardware and improves safety in experiments in case of system malfunction.

Second, findings from studies on human balance disturbances during walking and standing (Tan et al., 2020) suggest that rear-frame disturbances require forces exceeding the capabilities of typical laboratory setups. These disturbances must overcome the combined inertia of the bicycle and cyclist to generate meaningful instability, which presents practical implementation challenges.

Third, a handlebar-applied torque disturbance more closely approximates real-world balance disturbances than lateral pulls on the saddle or rear-wheel tire–ground contact point displacements.

Moreover, we expect that MAHD, determined through handlebar disturbances, is representative of responses to other impulse-like disturbances. Due to the strong dynamic coupling of lean and steer angles, disturbances applied elsewhere on the bicycle are likely to induce comparable steering responses. Prior work has shown that steering into the direction of the fall is the most effective and precise recovery strategy following impulse-like disturbances (Kooijman et al., 2011; Schwab et al., 2012). Therefore, improvements in MAHD observed for handlebar torque disturbances are likely to generalize to other types of disturbances, even if the specific threshold values differ. Nevertheless, future research should evaluate the sensitivity of MAHD to disturbance type and location to confirm its generalizability.

3.3 Maximum Versus Small Disturbances

Our proposed indicator quantifies the maximum disturbance a cyclist can recover from rather than the response to small disturbances. The latter approach is commonly used in dynamic system stability analysis (Meijaard et al., 2007; Kooijman et al., 2011; Schwab et al., 2012, 2013), where the system is linearized around a steady-state trajectory. Stability is then inferred from the eigenvalues of the linearized equations, which indicate how the system responds to small deviations from equilibrium.

While analytically convenient, this method has important limitations for real-world fall prediction. First, large disturbances often result in lean and steering angles that exceed the valid range for linear models. As shown by Basu-Mandal et al. (2007), non-linear bicycle dynamics begin to diverge from linear approximations at larger deviations, particularly beyond lean angles of approximately 45°. Second, even for minor disturbances, linear bicycle dynamics models describe only the lateral dynamics (e.g., lean and steer angle) but not the global trajectory or spatial constraints. In real-world crashes, cyclists must recover within finite lateral boundaries—something linear models do not account for (Meijaard et al., 2007).

Third, human control responses are themselves nonlinear and task-dependent. In gait, disturbance responses vary with magnitude and context (Gerards et al., 2017; McCrum et al., 2022). We expect similar behavior in cycling: some individuals may proactively react to small disturbances, while others delay the response until deviations cross certain thresholds. Moreover, differences in strength, reaction time, or attentiveness can limit the individual's maximum recovery capacity.

Given these factors, we adopted the maximum allowable disturbance as a more direct and interpretable measure of fall risk. If future studies validate that small-disturbance responses reliably predict fall likelihood, these could offer a safer and more convenient basis for ex-ante evaluation. We recommend further research in this direction.

3.4 Experimental Evaluation

The proposed experimental setup offers a controlled, repeatable, and safe environment in which to observe actual fall events. A key advantage is its ability to expose participants to near-threshold disturbances without risking injury. This enables systematic ex-ante evaluation of intervention effectiveness by measuring changes in the MAHD.

However, environmental validity remains a limitation. Although the mechanical dynamics of treadmill cycling at constant forward speed resemble those of real-world cycling, the absence of natural sensory cues such as optical flow and the laboratory environment may alter rider behavior. Participants will likely adopt a more cautious or attentive riding style, leading to conservative MAHD estimates.

To date, the environmental validity of treadmill cycling has not been empirically established. Field experiments could improve realism but raise ethical concerns, as actual falls would be required. Similarly, while cycling simulators could offer a safe alternative, current systems lack the dynamic fidelity needed for high-precision balance recovery research (Sporrel et al., 2023).

To define the MAHD in human subject experiments, we selected the disturbance magnitude corresponding to a 50% probability of falling based on the fitted logistic regression model. This choice represents the midpoint of the binary outcome distribution and offers a neutral, data-driven reference point for comparing intervention effectiveness. Moreover, mathematically, the 50% point corresponds to the inflection point of the logistic curve, where the log odds equal zero, making it both conceptually and computationally convenient to estimate. While other thresholds (e.g., 25% or 75%) could be explored depending on the safety margins desired in specific applications, the 50% threshold provides a balanced and replicable basis for identifying the resilience limit of the cyclist–bicycle system. Future research could investigate how sensitive MAHD-based conclusions are to the choice of threshold probability.

3.5 Simulation Models

Simulation using bicycle dynamics and cyclist control models provides a fast and cost-effective alternative to experimental evaluation. These models are well-suited for testing a wide range of bicycle geometries and cyclist assistance systems. However, cyclist control models remain limited in their ability to incorporate intuitive changes in rider behaviors or training-induced changes. Improving their practical application remains an important direction for future work.

Fall detection in the transient analysis was based on threshold values for lean angle, steering angle, and lateral displacement. The threshold values were derived from empirical observations, physical reasoning, and engineering heuristics.

We used a 45° threshold for both lean and steering angles, reflecting the limit at which bicycle dynamics deviate from linear behavior and tire lateral traction is likely to be exceeded (L/V ratio = 1) (Basu-Mandal et al., 2007; Marquis & Greif, 2011). This provides a conservative and physically meaningful fall criterion under normal surface conditions. Crashes caused by surface slipperiness are beyond the scope of this study and may require different interventions such as improved winter road maintenance or tires with improved traction.

A lateral displacement threshold of 0.6 m was chosen based on observed cyclist spacing from the edge of the path in real-world conditions (Schepers et al., 2023). While some riders cycle closer to the edge (as little as 0.17 m), our conservative estimate accounts for the lateral space typically available to perform a recovery maneuver.

These thresholds are approximations and may influence the absolute value of the MAHD. However, we expect that relative differences across interventions will remain consistent. That is, if an intervention increases MAHD under one threshold set, it is likely to do so under others. Nonetheless, sensitivity analysis and empirical validation of these thresholds are recommended.

More realistic values can be obtained when a tire model, capable of lateral sliding, is included in the bicycle dynamics model. A validated tire-road interaction model, which can be included in the bicycle dynamics model, does not yet exist for bicycles although recent research is beginning to address this gap (Dell'Orto et al., 2024).

The reliance on empirical thresholds in the model-based estimation of the MAHD introduces uncertainty in its operational implementation. However, this constraint is not unique to the present work. Perturbation-based indicators in human balance and gait research likewise rely on empirically motivated fall criteria that are refined through iterative validation. Importantly, the conceptual definition of the MAHD does not depend on any particular threshold set, and experimental estimation does not require thresholds at all, as a fall can be observed directly. Recent experimental studies confirm that the MAHD can be measured robustly in human subjects, providing an empirical foundation for calibrating and validating model-based analyses (Reijne et al., 2025). Nonetheless, further sensitivity analyses and validation against real-world cycling conditions remain important directions for future research.

3.6 Practical Implications

The proposed approach fills a current gap in cyclist safety research. Interventions that aim to improve balance recovery—as opposed to reducing collision probability or impact severity—cannot currently be evaluated systematically in an ex-ante framework. The MAHD offers a general, quantitative performance indicator for this purpose.

In practice, the MAHD can be used to evaluate interventions by comparing its value before and after the intervention is applied in a controlled test or simulation—for example, measuring changes in MAHD after a cyclist completes a training program, rides a bicycle with modified geometry, or cycles in a simulated environment with more lateral recovery space or sloped curbs. An increase in MAHD indicates improved balance recovery capacity and, by extension, a lower likelihood of falling following disturbances.

The MAHD allows systematic comparison of training programs, bicycle design modifications, and infrastructure designs for curbs and road shoulders. Practitioners could use MAHD to optimize interventions during the design phase, improving evidence-based decision-making. Researchers and policymakers could also use it to compare different intervention types and allocate resources more effectively. If validated and standardized, MAHD has the potential to reduce fall-related injuries among cyclists meaningfully.

3.7 Future Research

To strengthen the scientific foundation and practical application of the MAHD, several avenues for future research should be pursued. First, validation against real-world fall incidents and longitudinal data is essential to confirm its predictive power. Because controlled perturbations are difficult to reproduce safely and consistently in naturalistic cycling environments, such validation may rely more heavily on observational field data and longitudinal cohort studies, similar to approaches used in gait perturbation research (Sturnieks et al., 2013; McCrum et al., 2017; Rieger et al., 2024). Second, empirical data on real-world disturbance profiles—including magnitude, direction, and duration—should be collected to relate the estimated MAHD values (and changes in MAHD values) to real-world events. Third, the thresholds used to define falls in simulation (lean angle, steering angle, lateral displacement) should be subjected to sensitivity analysis and, where possible, derived from empirical data. Relatedly, further development of tire-road interaction models would improve the fidelity of fall prediction under varied surface conditions. Fourth, cyclist control models should be improved to simulate a broader range of behaviors and intervention effects, including those resulting from training. Fifth, to support the practical use of the MAHD in bicycle design, future research should investigate the sensitivity of the MAHD to key bicycle design parameters, such as geometry, mass distribution, steering stiffness, and tire characteristics. The MAHD can serve in these analyses as an objective performance function. Such systematic sensitivity analyses could reveal which parameters most strongly influence balance-recovery capacity, thereby providing actionable guidance for designers seeking to improve stability-related performance and enabling more efficient exploration of the design space. Finally, the environmental validity of treadmill-based experiments should be empirically investigated to ensure that lab-based MAHD estimates generalize to real-world cycling scenarios.

4. Conclusion

Falls resulting from disturbances are a common cause of serious cycling injuries. Despite their prevalence, current safety evaluation approaches cannot systematically evaluate the effectiveness of interventions aimed at improving balance recovery. This study introduced the Maximum Allowable Handlebar Disturbance (MAHD) as a novel, quantitative performance indicator to support the ex-ante evaluation of such interventions.

We proposed two complementary approaches to determine MAHD: controlled treadmill experiments and simulations using bicycle dynamics and cyclist control models. The experimental setup allows for safe, repeatable testing under controlled conditions, while simulation models enable efficient and broad exploration of interventions.

The proposed novel approach enables evidence-based development of training programs, bicycle design modifications, and infrastructure solutions such as curb and road shoulder designs. While further validation and refinements are needed, the MAHD lays the foundation for an approach to evaluate and compare balance recovery interventions before they are implemented in the real world systematically.

This contribution offers a step forward in the proactive design of cycling safety measures and holds promise for reducing fall-related injuries. Rather than replacing existing evaluation approaches, the MAHD is intended to complement them by providing a disturbance-based performance indicator that addresses intervention types for which current ex-ante methods offer limited predictive value.

CRediT contribution statement

Marco M. Reijne: Conceptualization, Formal analysis, Investigation, Methodology, Writing—original draft, Writing—review & editing. **Frans C. T. van der Helm:** Funding acquisition, Supervision, Writing—review & editing. **Arend L. Schwab:** Conceptualization, Investigation, Methodology, Supervision, Writing—review & editing.

Declaration of Competing Interests

The authors report no competing interests.

Declaration of generative AI use in writing

During the preparation of this work, the authors used OpenAI's ChatGPT in order to improve the readability and language of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Ethics Statement

No data was collected for this present study and was therefore exempted from ethical approval.

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