The Effect of Age on the Relationship between Speed and Swerving Behavior

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ABSTRACT

This study investigates the relationship between speed and swerving behavior, measured by the standard deviation of the lateral position (SDLP), with a focus on whether age moderates this relationship. To establish this data a questionnaire was used, and a naturalistic cross-sectional experiment was conducted comparing two groups: older cyclists aged 65 years and above ($N = 70$) and younger cyclists aged 20-28 years ($N = 16$). In this experiment, participants cycled straight ahead for a total of 600 meters, maintaining their usual cycling behavior, while their speed and lateral position were measured using GPS cameras. Data analysis involved examining correlations between age, speed and SDLP variability, as well as a linear regression analysis to explore the effect of speed on SDLP variability, and a second multiple linear regression to explore the effect of age on this relationship. The findings of this study suggest that speed has a significant effect on swerving behavior but age does not moderate this relationship, meaning that older and younger cyclists have comparable stability in steady-state cycling intervals. This study gives new insights in cycling stability and also offers ideas for future research to improve cycling safety, not only for older adults, but for the whole cycling population.

Keywords: age, bicycle, stability, speed, moderation, swerving behavior

The Effect of Age on the Relationship between Speed and Swerving Behavior

The Netherlands is known as a cycling nation, where bicycles play a crucial role in daily transportation, as the Dutch population uses a bicycle as mode of transport for 28% of all trips made (CBS, 2023). Despite the country's cycling culture, there is little research on how speed affects cyclists' behavior on the road, particularly in relation to their cycling stability. This knowledge gap is concerning, especially given the high number of cycling accidents involving older adults. It was found that 80% of accidents among older adults are linked to low cycling speeds (Dubbeldam et al., 2014). Worldwide around 60-95% of cyclists that are admitted to emergency departments are victims of single-bicycle accidents, in which no other party is involved. In the Netherlands, around 12,000 older cyclists require medical care due to such accidents each year (Dubbeldam et al., 2017a). A quarter of these single-bicycle crash casualties ride off the bicycle path, indicating the relevance of swerving behavior (Schepers et al., 2015, 2023).

Understanding how speed affects variation in lateral positioning (SDLP), a measure of stability, offers insights into swerving behavior, and therefore cycling safety. This paper investigates the relationship between speed and SDLP and explores whether age moderates this effect. Comparing age groups helps identify whether older cyclists face unique challenges or if broader patterns across age groups require safety interventions.

Quality of life

Beyond safety concerns, it is important to acknowledge the broader significance of cycling in maintaining independence and quality of life, especially for older adults. Cycling is not only a practical mode of transport, but also an activity that contributes to the physical and mental health, as well as the mobility of older adults. While driving a car also offers mobility, elderly pose risks due to slower reaction times and higher accident rates, often leading to reduced driving or to stop driving altogether (Doroudgar et al., 2017; Ragland et al., 2004; Ross et al., 2012). In contrast, (electric) bicycles offer a flexible solution and can be adapted to individual abilities, helping older adults stay independent longer (Leger et al., 2019; Leyland et al., 2019). Another way in which cycling can contribute to the quality of life of older adults is that physical activities like cycling can boost mental health, as lifestyle interventions can reduce depression (Marques et al., 2020). Research has also suggested that cycling provides broader benefits such as a stronger social network, increased physical activity, and better overall mental health, particularly for adults in rural areas (Abe et al., 2018; Tsunoda et al., 2015). Therefore, mobility should be maintained for as long as possible.

Understanding bicycle stability

To ensure this mobility is both sustained and safe, attention must be given to the factors that could influence safety, like bicycle stability. The standard deviation of the lateral position (SDLP) is often used to measure cycling stability (Schepers et al., 2023). Bicycle stability is primarily influenced by speed and bicycles are stable within a velocity range of 15 to 24 km/h. Outside of this range, maintaining balance requires greater steering input (Dubbeldam et al., 2014). At low speeds bicycles become laterally unstable, and at high speeds the bicycle stabilizes more easily (Schwab et al., 2012). Additionally, Schwab et al. (2012) found that at speeds exceeding 10 km/h, a bicycle becomes self-stabilizing, reducing the rider effort to maintain balance (Kooijman et al., 2011).

Age, speed and cycling stability

Given the role of speed in cycling stability and the accident rates among older adults, it is important to consider how the factor age influences speed and stability. Previous studies have highlighted the influence of age on cycling behavior. For example, factors like age and gender affect free flow cycling speeds (in which the cyclist is free to choose riding speed), therefore influencing lateral positioning (Yan et al., 2020). Older cyclists tend to ride at lower speeds compared to younger cyclists, this slower speed can lead to more instability because balance is more challenging to maintain at lower velocities, especially on conventional bicycles (Dubbeldam et al., 2017b; Schwab et al., 2018; Yan et al., 2020). This is also reflected in the fact that older adults use more control mechanisms than younger adults, like outward knee movements, for compensating stability (Bulsink et al., 2016). This challenge is compounded by the fact that older adults often have reduced cognitive and physical capabilities, making them more vulnerable to falls (Engbers et al., 2018; OECD, 2001).

The role of electric bicycles

In response to the previously mentioned challenges, the rise of electric bicycles (e-bikes) has introduced new possibilities for cyclists, especially for older adults, as more than half of them only ride on electric bicycles, as they allow for faster acceleration and higher speeds (CBS, 2023; RIVM, 2022). Electric bicycles offer advantages such as enhanced stability due to the additional power they provide, therefore making it easier for older adults to maintain balance and ride at higher speeds (Kooijman et al., 2011; Twisk et al., 2017). Pedelecs (a type of electric bicycle) were shown to be less stable while mounting compared to conventional bicycles, but the advantage of electrical support for stability kicked in during the acceleration towards the steady-state cycling phase, for all age groups (Twisk et al., 2017).

Older cyclists tend to make different speed choices and experience different mental workloads compared to younger cyclists, as they are more likely to adjust their speed based on the complexity of the traffic situation than younger cyclists (Vlakveld et al., 2015). When riding electric bicycles, older cyclists often ride faster than on conventional bicycles, while their mental workload remains unchanged. When comparing them to younger cyclists on electric bicycles, cyclists older than 65 tend to cycle slower (Schleinitz et al., 2017).

Research Aims and Hypotheses

By moderating speed and balance, older cyclists could achieve a more stable riding experience, making cycling a safer and more accessible mode of transportation. Fewer accidents and increased confidence while cycling would allow older adults to maintain their independence and mobility for longer (Leger et al., 2019; Leyland et al., 2019), while improving their quality of life. Therefore, the central focus of this experimental research is whether speed impacts swerving behavior, and therefore stability, of younger and older cyclists differently. The first hypothesis (H1) is that higher speeds lead to less swerving behavior. The second hypothesis (H2) is that age group (younger vs. older) moderates this effect, with older cyclists showing more swerving behavior on the road than younger cyclists. Understanding these differences could reveal how older and younger adults are affected by speed-related stability issues, potentially indicating a need for targeted interventions. The findings of this study could provide insight into cycling safety for older and younger adults.

Methods

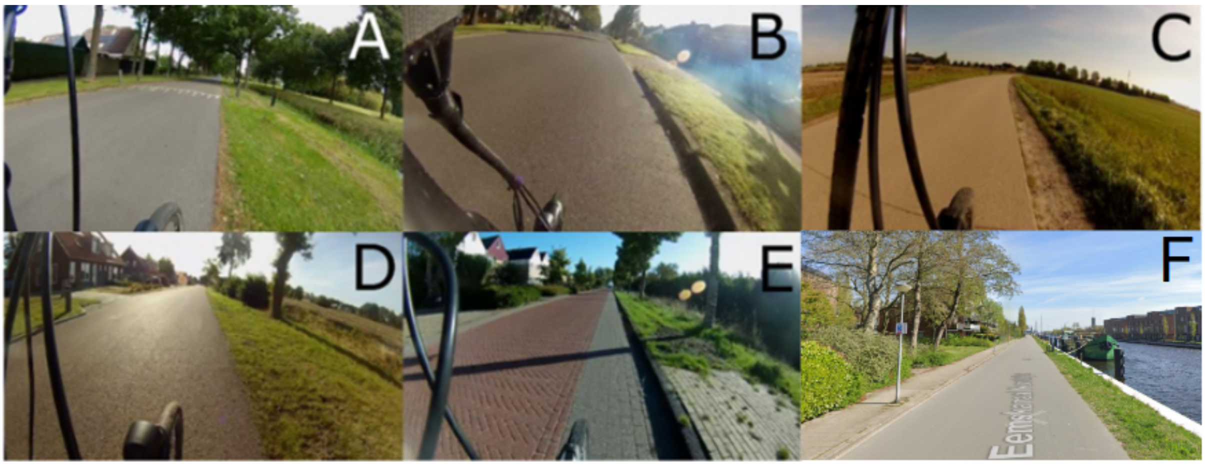
Participants

For this research, a group of older cyclists is compared to a group of younger cyclists. The older cyclists, aged 65 years or older and actively cycling, have been sampled through external recruitment by cooperation partners, *Karin Broer Fietsprojecten* and *Vriestyle*, these organizations are involved in cycling initiatives targeting older adults. Using their networks, they were able to recruit a pool of older cyclists for the study. Data collection involved different measurement moments at different locations in Friesland, in Figure 1 a visualization of these different locations can be seen. In this analysis, data from the first measurement moment is used for the analysis of the older participants. The younger participants (aged 18-30) were recruited through convenience sampling from the students' personal networks. The young participants that wanted to take part in the experiment registered through an online form. In this form, they were asked to provide their email address, age, and name. Data collection for the younger participants involved one location in Groningen (see Figure 1). For the older adult group, sessions were organized in groups, followed by a social activity such as a lunch and a recreational group cycling tour. The younger participants came individually with no social activity afterwards.

The experiment was conducted with a sample of 129 participants, consisting of 30 younger participants ($N = 30$) and 99 older participants ($N = 99$). However, because of technical difficulties due to invalid *SPLD* or *speed* data, 43 participants had to be removed. This leaves a sample of 86 participants, including 16 young participants ($N = 16$), and 70 older participants ($N = 70$). The ages of the younger group ranged from 21 to 28 years, with a mean age of 22.94 years ($SD = 1.98$). The group of younger participants consisted of 7 men and 9 women, no participants came with an electric bicycle. The ages of the older group ranged from 65 to 83 years, with a mean age of 72.1 years ($SD = 4.83$). The older group consisted of 34 men and 36 women. In the group of older participants, 57 participants came with an electric bicycle.

Figure 1

Impression of the different measurement locations in Friesland



Note. A: Oerterp (De Telle), B: Hurdegaryp (Easter omwei), C: Winsum (Stelpdyk), D: Mildaam (Molenlaan), E: Drylts-Ijlst (Sudergoweg), F: Groningen (Eemskanaal Noordzijde)

Design, procedure and materials

This study employs a naturalistic cross-sectional experimental design to investigate the effect of speed and age group (younger vs. older) on swerving behavior (measured by the standard deviation of the lateral position (*SDLP*)). Additional variables, such as (dis)mounting behavior were measured but excluded from this analysis. A visualization of the variables in this study can be found in Figure 2.

Before the experiment started participants had to fill in a questionnaire through Qualtrics with relevant questions to their cycling behavior and history, as well as the informed consent form. This online questionnaire was sent to the participants through email. In this email they also received a participant number and the time and place where they were expected. Furthermore, this study has been approved by the Ethical Committee of Psychology of the Rijksuniversiteit Groningen (PSY-2122-S-0271).

The experiment took place in half-hour time slots for each participant. The participants had to bring their own bicycle to the experiment and when the experiment started their bicycle was firstly equipped with a GPS camera (for the younger participants the GoPro HERO11 Black, for the older participants the Contour 2+) mounted on the right side of the handlebars (see Figure 3) and positioned in the middle of the calibration stick (see Figure 4).

Figure 2

A visualization of the variables in this study

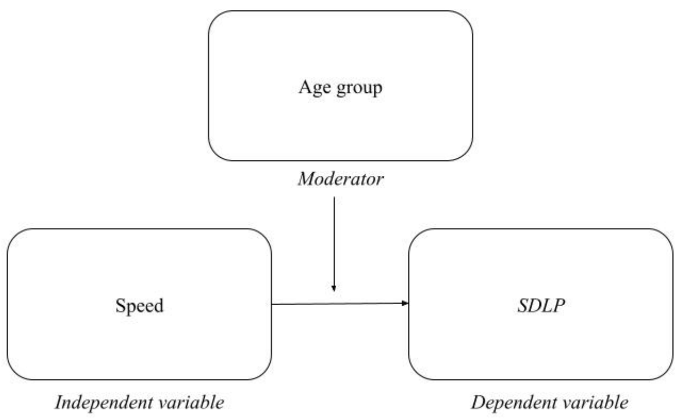


Figure 3

Visualization of the GPS camera that is mounted on the handlebars.

Figure 4

Visualization of the calibration pole

The bicycle was then held as upright as possible and moved backwards until the camera could capture the entire calibration pole. Each section of the pole is 25 cm, allowing the perspective to be standardized for the SDLP analysis. After the calibration, the participants were instructed to bicycle straight ahead for approximately 300 meters, then turn around and cycle back, maintaining their usual cycling behavior**.** All participants followed the same measurement protocol to ensure consistency.

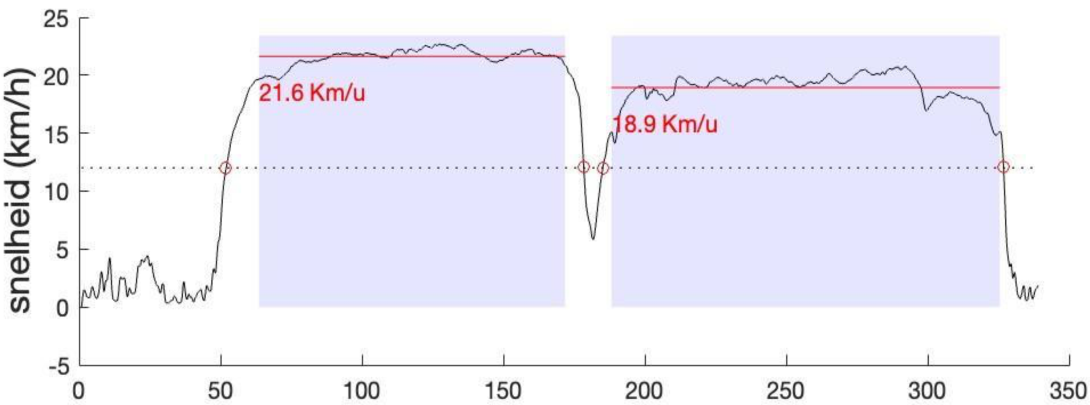
Data analysis

Speed analysis

Speed data were derived from the GPS readings captured by the camera mounted on the bicycle and subsequently analyzed in MatLab (MathWorks, version R2024b). For the older participants the sample frequency was measured at one time per second and for the younger participants this was 10 times per second (because of the different cameras used). The MatLab script utilized specific criteria to evaluate the speed profiles. To qualify as steady-state intervals, the analysis focused on segments where participants cycled above 12 km/h for the younger participants, and 10 km/h for the older participants. Within these segments, the first and last moments where acceleration equaled zero were identified and the period between these points was considered the steady state. Additionally, to qualify as steady cycling a minimum duration of 5 seconds was required, with shorter intervals than 5 seconds being excluded from the analysis. Lastly, a running average filter was applied, with larger values producing a smoother speed profile. With these criteria, MatLab can produce a speed profile and an acceleration profile. In Figure 5, an example of a speed profile is shown and in Figure 6 an acceleration profile is shown of the same participant. Using this script and data, through MatLab the maximum speed, the mean speed (of the steady-state intervals), the standard deviation and the acceleration can be computed.

Figure 5

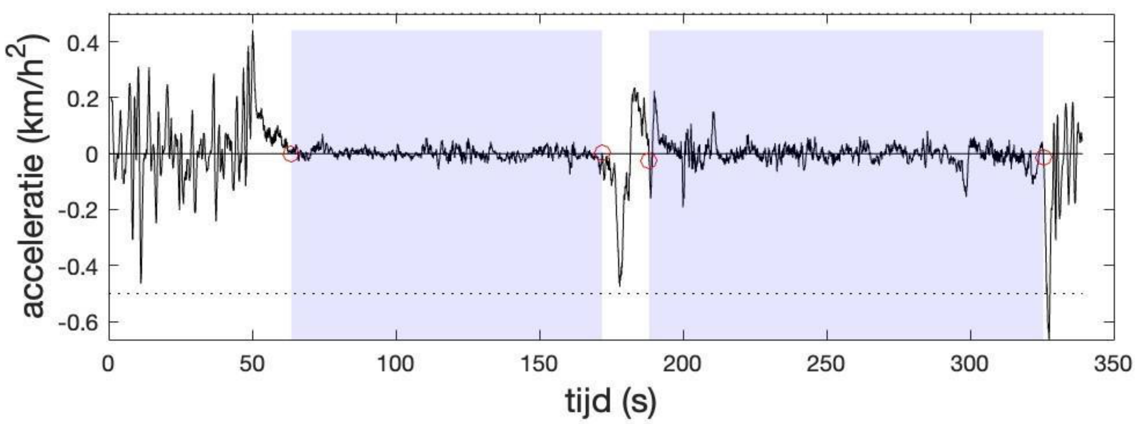
Example of a speed profile



Note. In this profile the line indicates the cut-off score of 12 km/h, the red circles indicate the first and last moments acceleration equaled zero. In this profile two steady-state cycling phases have been identified, the first one has a mean speed of 21.6 km/h and the second one has a mean speed of 18.9 km/h, in between these two steady-state cycling phases, the participant turned around.

Figure 6

Example of an acceleration profile

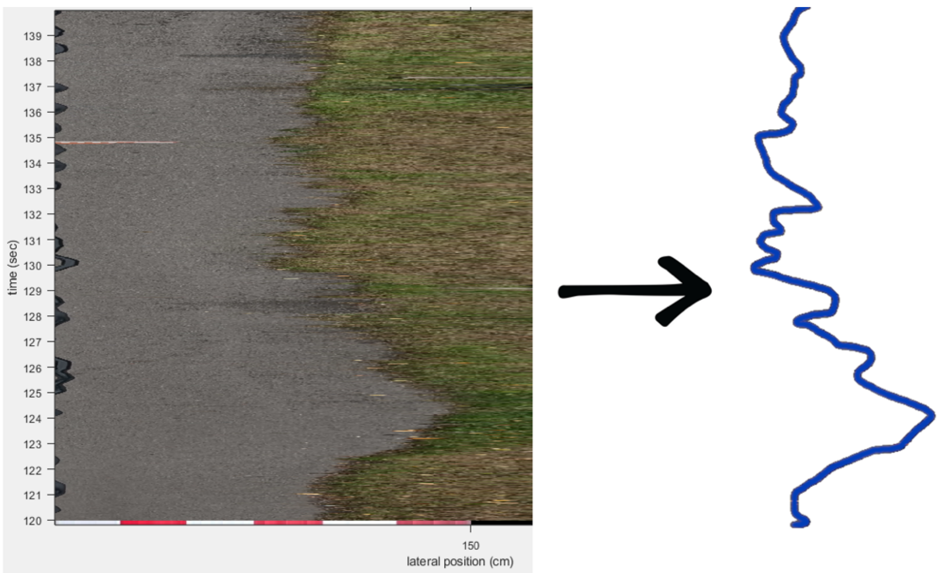


SDLP analysis

MatLab (MathWorks, version R2024b), along with the installed Image Processing Toolbox, Signal Processing Toolbox, and Computer Vision Toolbox, was used to convert the video footage into quantitative data. The analysis began by creating a calibration image (Figure 4) from the video to correct for lens distortion, which can be used as a reference for the analysis. The corrected video frames were then analyzed in MatLab over a 20-second segment, frame by frame. For each frame a horizontal strip was extracted, resulting in an image that plotted lateral road position against time (see Figure 7). This image clearly displayed the transition between the road and the roadside. Using GIMP (Version 2.10.38) a line was manually drawn at this transition to determine the lateral position at each point in time (see Figure 7). MatLab analyzed this line, producing the SDLP in centimeters and an Excel file containing the road distance over time.

Figure 7

Converting a MatLab image into a line using GIMP



Main analysis

To determine the effect of speed on the SDLP, and to examine the differences between younger and older cyclists, SPSS (IBM SPSS Statistics 27) is used. The analysis begins with a correlation analysis to investigate the relationship between speed, age and SDLP in the whole dataset, but also for the younger and older group separately. Then, a regression analysis is conducted to examine the relationship of speed and SDLP. Following this, a multiple linear regression analysis is conducted to examine the main effects of speed and age group (1.00 = young, 2.00 = old) as well as their interaction effect on the lateral position of cyclists to evaluate whether the influence of speed on the SDLP varies between younger and older cyclists.

Results

Descriptive statistics

The criterion of the cut-off score for the steady-state zones was changed from 12 km/h to 10 km/h for one of the younger participants and from 10 km/h to 8 km/h for one of the older participants so the steady-state zones could still be established.

The mean of the variable *speed* (the mean speed of the steady cycling states of every participant) of all the participants was 17.52 km/h ($SD = 2.36$), the *speed* of this sample ranged from a minimum of 11.78 km/h to a maximum of 22.79 km/h. The younger adults had a mean *speed* of 19.29 km/h ($SD = 2.03$), with a minimum of 15.47 km/h and a maximum of 22.16 km/h. For the older adults the mean *speed* was 17.12 km/h ($SD = 2.26$), with a minimum of 11.78 km/h and a maximum of 22.79 km/h. Levene's test indicated equal variances ($F(1,84) = .31$, $p = .58$). The t-test ($t(84) = 3.53$, $p < .001$) shows a significant difference in *speed* between groups in which the younger adults are faster than the older adults.

The mean *SDLP* for all the participants was 12.75 cm ($SD = 5.11$) and ranged from a minimum of 4.45 cm to a maximum of 34.50 cm. The younger adults had a mean *SDLP* of 10.92 cm ($SD = 3.44$), with a minimum of 4.45 cm and a maximum of 16.56 cm. In the group of older adults, the mean *SDLP* was 13.16 cm (*SD* = 5.35). The *SDLP* of the older adults ranged from a minimum of 6.64 cm to a maximum of 34.50 cm. Levene's test indicated equal variances ($F(1,84) = 2.00$, $p = .16$). The t-test ($t(84) = -1.60$, $p = .113$) shows that the groups do not significantly differ from each other.

Correlation analysis

The results of the correlation analysis show a significant correlation between the variables *speed* and *age* with a Pearson correlation coefficient of $r = -.37$ ($p < .001$), this shows that as a participant generally is older, *speed* will decrease. The variables *SDLP* and *speed* have a significant negative correlation ($r = -.26$, $p = .017$), this means that as the variable *speed* increases, *SDLP* tends to decrease. The correlation between the variables *SDLP* and *age* is non-significant ($r = .19$, $p = .08$; see Table 1).

Table 1

Descriptive statistics and Correlations for Study Variables

	1	2	3
1. SDLP	-		
2. Speed	-.26*	-	
3. Age	.19	-.37**	-

Note. *p < 0.05, **p < .001*

For the group of younger adults, the correlation between the variables *speed* and *SDLP* was non-significant ($r = -.10$, $p = .71$). For the group of older adults, the correlation between the variables *speed* and *SDLP* was also non-significant ($r = -.23$, $p = .06$).

Regression analysis

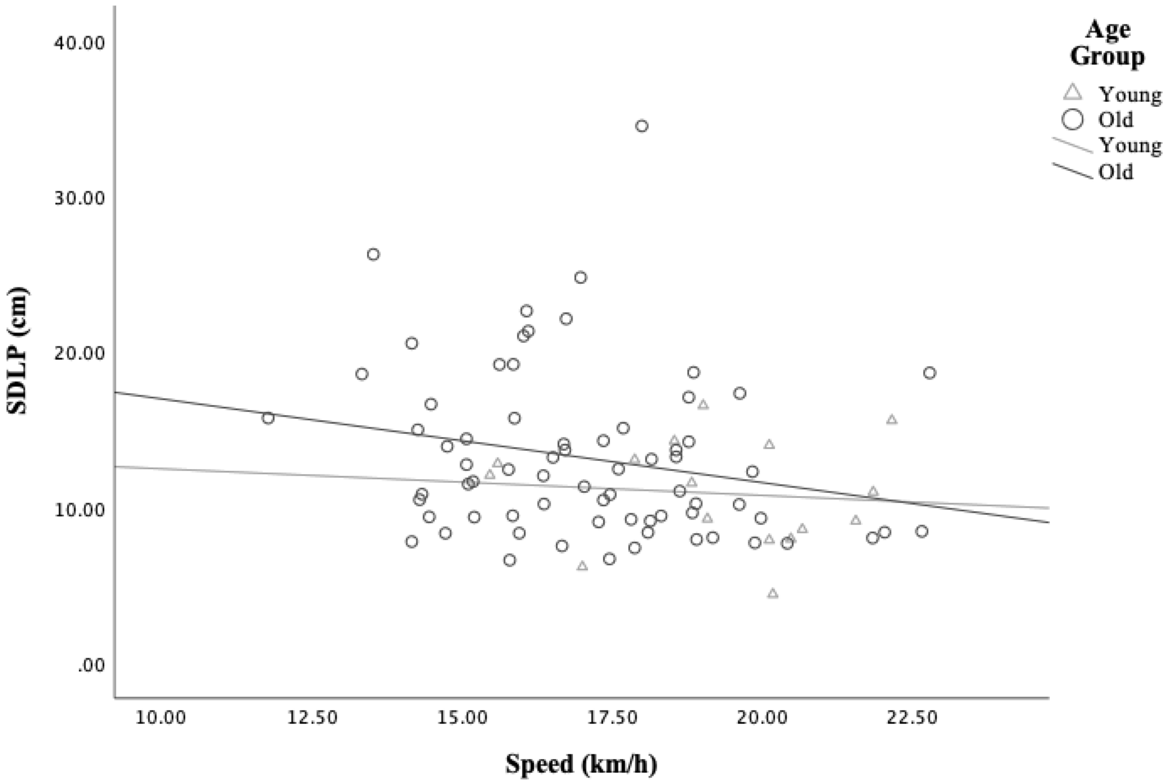
Before starting the analysis, all the assumptions of linear regression were checked. The assumptions of normality and homoscedasticity are met. Additionally, assumptions regarding outliers, influencers, and multicollinearity were checked. All the assumptions were met. A more detailed description of the assumptions can be found in the appendix (Appendix A).

In the first regression model the influence of the independent variable *speed* on the dependent variable *SDLP* is analyzed. A significant effect was found for speed on *SDLP*, with the coefficients *intercept* = 22.46 and *speed* = -.55. This model has an R^2 = .066 ($F(1,84) = 5.90$, $p = .02$). This model explains the variance of the relationship between *SDLP* and *speed* with 6.6%.

In the second regression model the potential moderating role of age on the relationship between *speed* and *SDLP* is tested by adding the independent variable *agegroup* and the interaction term *agegroup*speed* as an independent variable. The variable *speed* is non-significant in this model ($p = .88$), the variable *agegroup* is non-significant in this model ($p = .54$) and the interaction term *agegroup*speed* is also non-significant in this model ($p = .60$). The second model has a ($F(3,82) = 2.26$, $p = .09$), this suggests that there is no significant effect of *agegroup* on the relationship between *speed* and *SDLP*. The Error Mean Square value is 24.97, suggesting a considerable amount of unexplained variance in *SDLP*, which further weakens the model’s explanatory power. The results of this regression analysis are visualized in a scatterplot in Figure 8. In Figure 9 a boxplot is used to further illustrate the differences in *SDLP* between younger and older participants.

Figure 8

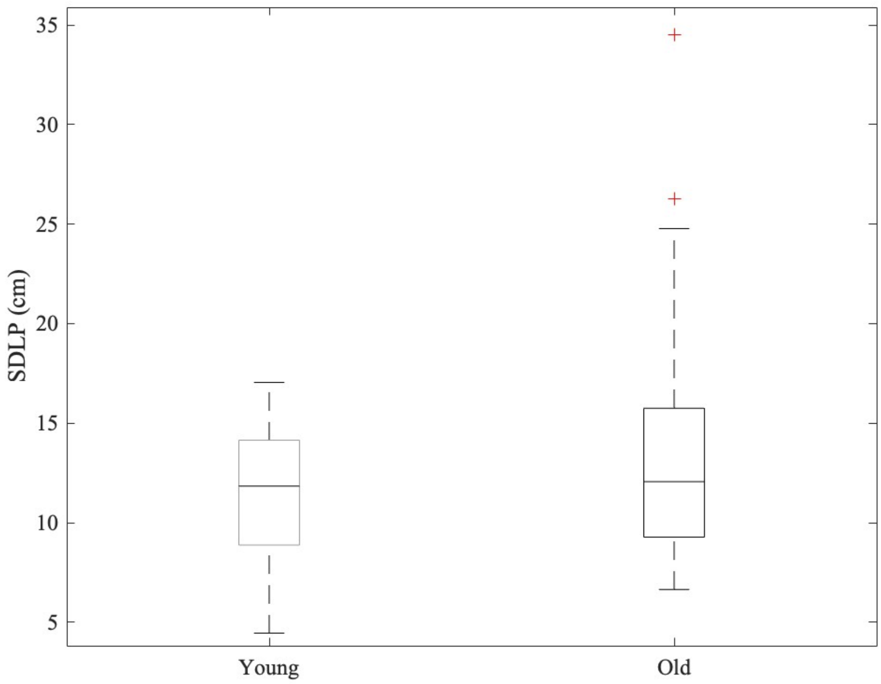
Scatterplot of the variables speed and SDLP



Note. This scatterplot shows the relationship between speed and SDLP for both age groups. The regression lines of young and old participants are shown separately to visualize the interaction of these two variables. For both groups a negative relationship can be seen but for older adults this relationship is stronger than for younger adults.

Figure 9

Boxplot of the variable SDLP (cm) for both age groups



Discussion

This research explored the relationship between speed and SDLP, specifically focusing on a moderating effect of age (younger vs. older adults), using multiple linear regression. The first hypothesis proposed that speed would be negatively related to swerving behavior (SDLP), meaning that higher speeds would lead to less lateral deviation and therefore more stability. The results did support what was hypothesized. This finding aligns with previous research that highlights the stabilizing effect of speed on bicycles (Schwab et al., 2018). The second hypothesis suggests that age (young vs. old) would moderate the relationship between speed and swerving behavior (SDLP). The second hypothesis was not supported in this study. The results of this study give more insight in cycling behavior of younger and older adults.

Theoretical and Practical implications

The findings from this study are in line with previous research from Schwab et al. (2018) that speed is a stabilizing factor. However, speed only predicted the variance in *SDLP* with 6.6%, which suggests other factors also play a role. As mentioned before, a bicycle becomes self-stabilizing after 10 km/h, reducing the rider effort to maintain balance (Kooijman et al., 2011; Schwab et al., 2012). As all participants cycled above this threshold, this could be an important reason for more stability. Dubbeldam et al. (2014) also mentioned that the bicycles are stable within a velocity range of 15 to 24 km/h. It could be true that speed is the most important stabilizing factor, but while in this stability range, or above the self-stabilizing threshold of 10 km/h (Schwab et al., 2012), changes in speed become less relevant for stabilizing. In this study the variable *age* (younger vs. older adults) was tested as moderator of the relationship between *speed* and *SDLP*. The findings of this study suggest that age does not influence this relationship, as adults demonstrated comparable stability to younger cyclists, despite the fact that their mean speed is lower. This finding challenges the common belief that older adults inherently experience greater cycling instability due to physiological or cognitive decline (Engbers et al., 2018; OECD, 2001). This could be contributed to the self-stabilizing effect of the bicycle as well. However, previous research has also shown that older adults show different balance strategies than younger adults, like outward knee movements (Bulsink et al., 2016). These compensation strategies could also play a factor when it comes to stabilizing the bicycle.

Practically, this means that cyclists should be encouraged to maintain certain speeds or stay in a certain stability interval on straight roads, but this still requires more research before implementing. Electric bicycles could offer a promising solution, as the electric assistance feature can help cyclists reach the necessary speed, minimizing instability and improving their cycling experience. However, electric bicycles are still less stable while mounting, and during low velocities (Twisk et al., 2017). The ‘SOFIE’ bicycle by Dubbeldam, et al. (2017b) is the first attempt at an electric bicycle that is stable during mounting and at low velocities. Moreover, promoting cycling among older adults is not only feasible, but also essential. Public health companies could leverage these findings to encourage cycling as a safe and effective form of exercise while maintaining physical health and mobility. By aligning these practical and theoretical implications cycling safety can be improved but can also foster greater confidence and participation among cyclists of all ages.

Strengths, limitations and future research

This study offers several notable strengths. First, it provides empirical support for the relationship between speed and SDLP, and this study contributes to the understanding of cycling stability across different age groups. By focusing on both older and younger cyclists, the study highlights behavioral, but also mechanical factors influencing SDLP. Second, the experiment lies in a realistic setting. Participants in this study cycled in a real-world environment. They rode on their own bicycles, at their own chosen speeds, while interacting with actual environmental factors like wind and oncoming traffic. This setup offers a perspective on how cyclists behave under natural conditions, therefore adding a layer of ecological validity to the study.

Despite these strengths, the study has several limitations. While the real-world setting enhances the realism of the study, it also introduces variability that could not be controlled entirely. For instance, wind direction and wind speed may have impacted the comparability of the results, as they varied each measurement day. For example, younger cyclists showed lower speeds on their way back because of strong winds. Schwab et al. (2018) found that crosswinds could affect bicycle stability, and could increase the effort of a cyclist to remain stable. In future studies, controlled laboratory settings could minimize the influence of factors as wind, allowing researchers to isolate specific criteria affecting speed and stability.

Another consideration is the population of cyclists that was studied. The older adults that participated were relatively fit and active, meaning they might not fully represent the broader group of older cyclists, for instance those with reduced balance, cognitive function, or physical fitness. Similarly, the younger participants were recruited through convenience sampling through the students' network, which could result in a biased sample towards more active younger cyclists. Future studies should include a more diverse sample to improve the generalizability of findings. A broader range of participants, particularly older cyclists with varying level of physical fitness or balance ability, would provide deeper insights into the effect of age on stability. Longitudinal studies may also provide insight into how age-related changes in balance and cognition influence cycling stability over time.

Finally, the cycling routes used in this study were relatively straightforward and flat, with no turns or obstacles. While this was a strength in terms of isolating the effects of speed on lateral stability, it leaves open questions about how cyclists behave in more complex environments. For example, cycling through intersections, navigating turns or riding on uneven terrain might place greater demands on balance and stability for older adults (Bulsink et al., 2016). Building on this study, future research could investigate the interaction between speed and swerving behavior in more challenging environments. For instance, they could examine how different terrains, like uneven paths, or urban settings could impact stability. Including these factors in future research could present a more complete picture of how cyclists of different ages manage stability in diverse real-world situations. Additionally, investigating the relationship of age and swerving behavior in low-speed settings, below the self-stabilizing threshold of 10 km/h could also provide more insight.

Conclusion

This study explored the relationship between speed and swerving behavior, and if age (younger vs. older adults) impacted this relationship, to gain more insight into the cycling behavior of different age groups. This study confirms that higher cycling speeds are associated with reduced lateral deviation, therefore emphasizing the stabilizing effect of speed. However, the speculated moderating effect of age on the relationship between speed and swerving behavior was not observed in this study. In conclusion, this study found that cycling stability between older and younger cyclists during steady-state cycling intervals is similar.

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Appendix A: Assumptions for Main Analysis

Figure A1

Normal PP-plot of the residuals of the independent variable speed

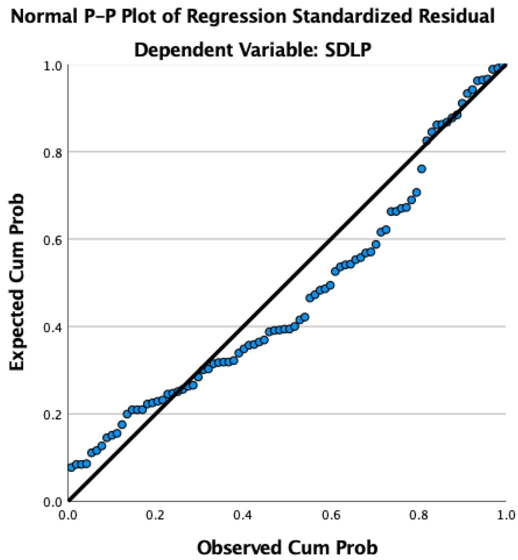


Figure A2

Normal PP-plot of the residuals of the independent variable speed

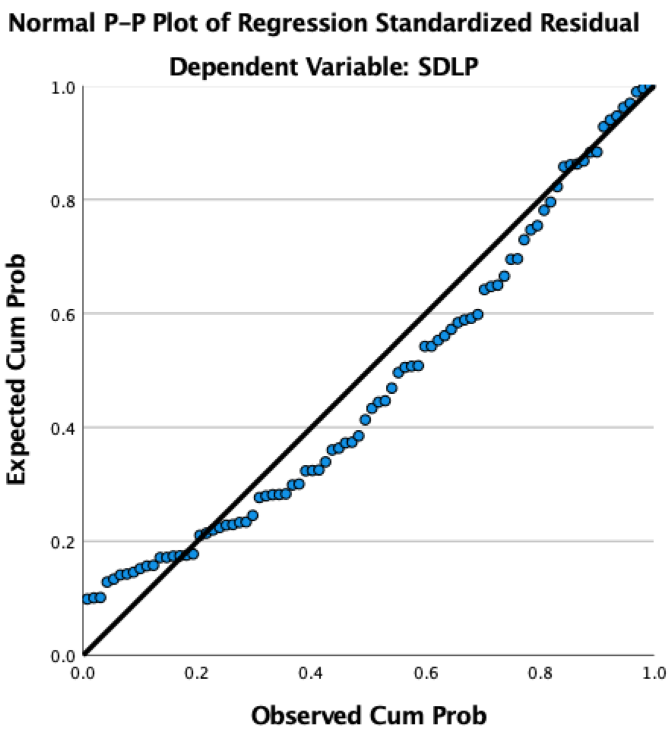
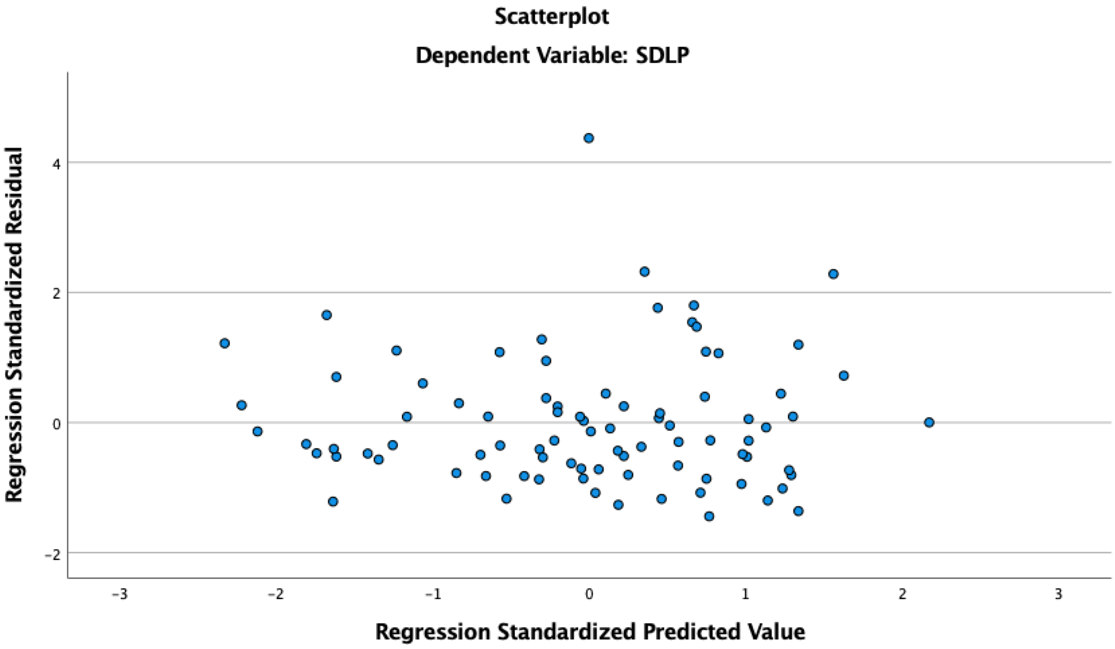


Figure A3

Scatterplot of residuals of the independent variables agegroup and speed



A5 Outliers and Influencers

The *speed* data contains no outliers, in the *SDLP* data one outlier of 34.50 is identified. However, these outliers are not influencers (max. *CD*=.09), which is below 1, and therefore acceptable (Kutner et al., 2005).

A6 Multicollinearity

The multicollinearity assumption is not violated (*VIF* = 1.15, with at *Tolerance* of .87). Which is <5, therefore acceptable (Kutner et al., 2005).

Appendix B: Data collection and storage

The data collection of this experiment was carried out using the method described in the methods section of this research paper, this study has been approved by the Ethical Committee of Psychology of the Rijksuniversiteit Groningen (PSY-2122-S-0271).

All collected data used for this research have been stored on the protected Unishare environment of w.a.kruise@student.rug.nl with permission of B. Sporrel. During data processing, the data was stored locally. These files were deleted upon completion of the study.