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Research article

Bicycling tasks relation to stability measures during alcohol intoxication

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Abstract: Bicycling accidents are a major traffic safety problem and are deemed 'an unacceptable human and social price for EU citizens'. One of the major causes for bicycling accidents is loss of balance. A related influencing factor is alcohol intoxication. It is a primary, long term, safety objective to develop safety systems for the cyclist. The present work aimed to understand how to measure cyclists' instability via steering and leaning inputs, while considering that steering and leaning might vary depending on the cycling task being performed. Of 28 participants, 19 were given doses of alcohol up to 1.0‰ and 9 remained sober (control group). Breath alcohol concentration was measured. The participants repeated the cycling test track session five times (with each block lasting 35 minutes). The track session contained three different tasks: cycling slalom, straight, and slowly. Speed, yaw rate, and roll rate were assessed continuously. Yaw rate and roll rate were relatively sensitive for the different cycling tasks. The threshold level of the angular velocity measurements was related to the cycling task performed. Alcohol intoxication at 0.7‰ had a significant impact on performance. The rather simple measurements used can detect instability. Instability should be measured differently depending on the cycling task performed. The study represents a small step towards a safety system for cyclists.

Keywords: alcohol intoxication, roll rate, ratestability, yaw rate

1 Introduction

Cycling crashes are one of the traffic safety issues that need to be addressed within a Vision Zero paradigm (the principle that no one should die or get seriously injured in the transport sector). In Sweden, cycling accidents are the most common traffic accident type (Rizzi et al., 2020), with over 23 000 cyclists seeking care at emergency hospitals every year (MSB, 2013). In Europe, there were 19 450 cycling fatalities between 2010 and 2018 (Adminaité-Fodor & Jost, 2020). At the same time, cycling as an active transport mode provides major health benefits, with electric bicycles making it easier to cover larger distances and enabling increased use by older adults for instance. However, increasing (electric) bicycle use is accompanied by increased fatalities and injuries across all age groups, particularly older adult cyclists. People aged above 65 years account for 44% of all cyclist deaths in the EU. A recent review by Utriainen et al. (2022) showed that 52%–85% of bicycle injuries were caused by single bicycle crashes (i.e. falls and impacts not involving contact with another road user). The European Vision Zero white paper (EC, 2020) states a target goal of close-to-zero road fatalities and serious injuries by 2050, but the 2020 target of a 50% fatality reduction has already been missed. Not reaching this target is deemed 'an unacceptable human and social price for EU citizens' (EC, 2020).

One major cause of bicycle crashes is loss of balance (Alizadehsaravi & Moore, 2023). Cyclists lose balance for several reasons, such as a slippery road surface (ice, leaves, water etc.), and to avoid collisions and obstacles. Given the ambition to reduce cycling crashes related to imbalance, the understanding of cycling stability needs to be improved. The literature on cycle stability (Edelmann et al. (2015): lean and steering torque; Huertas-Leyva et al. (2018): braking behaviour; Moore et al. (2010): body control model; Rekilä & Klein-Paste (2016): friction in wintertime; Schwab et al. (2012): upper body leaning and twisting; and Twisk et al. (2017): mounting) reveals relatively complex models, but all studies included leaning and steering (roll and yaw) measures. The relative contributions of leaning and steering remain somewhat unclear (Andersson et al., 2023). When cyclists turn left or right (Moore, 2012; Moore et al., 2010), most use the handlebar and their body to get where they want. The management of the handlebar and the body is closely related. However, the importance of leaning and steering might vary in different cycling tasks such as cycling straight, cycling slalom, or cycling slowly.

In Edelmann et al. (2015), a bicycle rider control model was exemplified using a cornering manoeuvre at the speed of 3 m/s (10.8 km/h) and entering a curve with a constant curvature (κ = 0.11/m). Edelmann et al. (2015) concluded that lean torque input, in contrast to steering torque input, has a marginal impact. The literature on cycling stability (balance) also reveals that speed and skill are important. At lower speeds, novice and skilled cyclists show similar balance performances, but at higher speeds, skilled cyclists use more lean control and less steer control (Cain et al., 2016). Alcohol intoxication also affects balance, as shown by Andersson et al. (2023), whereby alcohol intoxication increases instability substantially. In the latter study, the participants started cycling sober, but were then administered alcohol until they reached a 0.8‰ alcohol level. Participants cycled at the speed of 5.55 m/s (20 km/h) on a wide treadmill (cycling straight); the results showed that leaning and yaw rates were considerably affected. The literature on alcohol intoxication and crashes reveals a clear pattern; specifically, alcohol intoxication is a significantly important factor in crashes (De Waard et al., 2016) and stability is substantially affected (Andersson et al., 2023). We do not suggest that instability or alcohol is the only cause for crashes, but imbalance and crashes is assumed to be related (Lefarth et al., 2021; Berk et al., 2022). We still need a better understanding of these relations and an understanding of stability during different bicycling tasks (when intoxicated) is one step towards increased bicycling safety.

A long-term objective of research on stability is to reduce crashes; one means of achieving this is to inform the cyclist about instability in different ways. The practical implications of understanding how leaning (roll) and steering (yaw) are related to stability would help stimulate the development of an advanced rider-assistance system (ARAS) that could be used by the cyclist to avoid crashes (or hazardous situations). If a cyclist is given information about locations on their route that are 'problematic', they could choose to take another route or exercise greater caution when passing through those locations. Information could be collected by instrumented bicycles, such that when a cyclist experiences an instability, over a certain threshold, this information is shared, along with the location. This information can be shared with other connected cyclists; furthermore, municipalities with maintenance responsibilities can take action to address the issues. Thus, the information could be used to reduce the number of balance-related crashes that occur at specific locations.

The present experiment aimed to measure cycling stability in a 'valid' way when cyclists performed different tasks. 'Valid' here refers to a pragmatic perspective in terms of developing an ARAS that is affordable, with 'click on' functionalities for cyclists (a standalone system that can be used on multiple bikes). Whether or not an ARAS with this functionality would reduce the number of instability-related crashes is, however, an empirical question that is not addressed here

2 Aim

The specific aim of the present experiment is to develop an understanding of how to measure cycling stability when a cyclist performs different tasks. As increased alcohol concentration decreases our stability (Modig et al., 2012; Andersson et al., 2023), differences between an experimental group, with an increasing alcohol concentration (from 0‰ to approximately 1.0‰), and a sober control group can indirectly be used to identify suitable measures of cycling stability. The sensitivity of different measures (roll and yaw) will hence be evaluated for different cycling tasks, i.e. cycling straight, slowly, and slalom, where three sensitivity levels will be evaluated for each of the three tasks based on distribution curves for yaw and roll rates (see method section for details).

3 Method

3.1 Participants

A total of 28 participants were included in the experiment: 19 participants were in the experimental group, which was provided with alcohol, while 9 participants were in the control group, which remained sober throughout the experiment. The experimental group, which consisted of 10 women and 9 men, were aged 21–35 years (average age of 30 years). The control group, which comprised four women and five men, were aged 21–33 years (mean age of 29 years). Participants in the experimental group received SEK 1000, while those in the control group received SEK 750, as a token of our appreciation.

Participants were recruited using a Facebook advertisement. The advert directed people who were interested to a VTI (Swedish National Road and Transport Research Institute) website (with a link to a survey). If the survey responses did not match the selection (inclusion and exclusion) criteria, the person was directed to a web page that informed them of this. Those who matched the criteria were asked to provide contact details so we could get in touch.

The inclusion criteria were: being resident in the Falun/Borlänge area, aged 20–35 years, having good health for drinking alcohol and for cycling, having a regular cycling habit (preferably at least twice a week during the snow-free season), being a moderate consumer of alcohol, and having experience of cycling under the influence of alcohol (at least once during the snow-free season).

Exclusion criteria were: pregnancy, diseases that can lead to an increased health risk with alcohol consumption, a body mass index of under 18 kg/m^2 or over 30 kg/m^2, a history of aggressiveness or depression when consuming alcohol, a history of hazardous or harmful use of alcohol according to the Swedish version of AUDIT (World Health Organization's The Alcohol Use Disorders Identification Test), and insufficient Swedish language skills (i.e. not being able understand or communicate satisfactorily with the experiment leaders).

Those who provided contact information were called by an experiment leader who ensured that these individuals had understood what the study was about and what was expected of them. Those who, after this conversation, were still interested in taking part, were scheduled for participation in the experiment. Three days prior to their scheduled participation time, the individuals received an email with a reminder of the meeting time and place. They were also asked to try and ensure they got enough sleep the night before, to refrain from alcohol 24 hours before the experiment, to eat a solid meal before the experiment, to wear suitable clothes, and to bring their own bicycle helmet, gloves, and other suitable protection if they so wished (especially elbow protection). The email also included a form to be signed by a close relative or friend, who guaranteed to take care of the participant after their participation until they were sober.

3.2 Pilot study

A small pilot study was conducted prior to the actual data collection. Using convenience sampling, three men aged 27–56 years were recruited. All three individuals were provided with alcohol as they underwent the procedure as described below. The pilot study aimed to test the protective gear, bicycles, test track and all instruments to be used, and to check that the estimated session time was sufficient.

3.3 Procedure

The data collection was carried out in a disused paved parking space in Falun, Sweden, on May 9–15, 2022. Most sessions were conducted in parallel, with two participants at a time. Each session began with one of the experiment leaders welcoming the participants and asking them to identify themselves. The participants were once again informed about the study and given the opportunity to ask any questions. They were subsequently asked to sign a consent form, and to send a reminder SMS text message to the individual who had guaranteed to collect and take care of them after their participation until they were sober.

All participants were weighed and each then completed Zuckerman's Sensation Seeking Scale Form V (SSS-V) (Zuckerman et al., 1978). The results of this scale are not presented in the current paper. The experiment leader calculated how much vodka each participant would need to drink to achieve the target values of 0.30‰, 0.75;‰, and 1.00‰ alcohol level, and then maintain a 1.00‰ alcohol level, taking the participant's gender and weight into account (Alkompassen, 2019).

The choice of alcohol level target values represented a balancing act between providing the participants with sufficient alcohol to produce measurable effects (Hartung et al. (2015), for example, saw non-significant deterioration of gross motor skills until participants' alcohol level was 0.8‰), and to avoid nausea and other negative side effects as much as possible. The experiment leader randomised the participants into groups, so that one out of three participants was included the control group. However, the participants themselves did not find out which group they had been assigned to until they had ended their participation. Finally, the participants were asked to visit the toilet (women who might be pregnant were offered a pregnancy test in connection with the toilet visit), before being asked to put on a bicycle helmet, gloves and other protection. The bicycle saddles were then adjusted and the participants, together with the experiment leader, cycled a couple of hundred meters to the test tracks (see Figure 1).

Once at the test tracks, the participants were each assigned a specific test track, where an experiment leader welcomed them. The participants started the test phase by taking alcohol breath tests, to ensure they were not under the influence of alcohol before the test session began. Next, the experiment leaders went through the cycling procedure with participants, including safety rules. Afterwards, the participants first had to walk the test tracks and then practice cycling on the test tracks with the instrumented bicycles for about 10 minutes. Once participants had finished the training, they were given the opportunity to adjust the bicycle saddles further. The participants were then given instructions and time to practise on working memory capacity (N-back test) and reaction time tests. Finally, the participants were given the opportunity to pose any remaining questions before the actual trial started.

The experiment consisted of five identical blocks, with each block lasting 35 minutes. Each block started with cycling four laps on the test track (10 minutes), while the experiment leaders recorded general cycling performance. The cycling was followed by a mouth rinse and an alcohol breath test. Then, the participants' perceived influence of alcohol, their self-estimated cycling ability, their working memory capacity, and their reaction time were measured. (These measurements are not presented in the current paper.) Afterwards, the participants in the experimental group were provided with alcohol (in the form of vodka, ginger tonic, and cucumber, in an attempt to mask the taste of alcohol – which failed). The control group was provided with a non-alcoholic drink (in the form of ginger tonic and cucumber, to mask the lack of alcohol). Both groups had a rest period before starting the next block. The time from when participants received a drink until the start of the next block was at least 15 minutes, to allow time for the alcohol to be absorbed. In addition to the allocated drinks, participants had free access to soft drinks, water, chips, cheese bars, and candy. Because the drink was given at the end of each 35 minute block, all participants were sober when they completed the first block; this initial block thus acted as a baseline (Time 0).

When the last block was completed, the participants completed a post-experiment survey. The survey contained questions about attitudes, norms, control, intention, and previous behaviour regarding cycling in real traffic when they had felt equally or more affected by alcohol as in this experiment. Finally, the SSS-V sensation-seeking questions were repeated before the experiment came to an end. When the post-experiment survey was completed, the participants in the control group were informed that they had not been given alcohol during the experiment and they were free to leave. Participants in the experimental group were offered water, tea, coffee, sandwich, and fruit. After an hour, they had to take another alcohol breath test. If the test showed that their alcohol level had started to decrease, they were allowed to leave the test track together with their close relative or friend, who had guaranteed to take care of them until they were sober.

3.4 Cycling tasks and test track

Cycling stability was measured in terms of roll rate and yaw rate (angular velocity measurements) for three different tasks, with three different cut-off values for each task. Task 1 involved a cycle slalom around nine plastic cones. For Task 2, participants had to cycle as straight as possible on a drawn line in the centre of the cone-shaped marking. In Task 3, participants had to cycle as slowly as possible (see Figure 1). Data were collected using gyro sensors and stored in a VBOX data logger mounted on the bicycles.

Two test tracks, inspired by Hartung et al. (2015), were built with the short sides facing each other in a disused parking space. Between the test tracks, three cabinet trailers were placed for the protection of the participants, and for the protection of equipment from the weather in-between cycling sessions. These trailers also functioned as a screen, so that the participants could not see each other when tested in parallel.

The test track began with the slalom course, with nine plastic cones placed at a decreasing distance, from 4.0 to 1.5 meters (Task 1: cycling slalom). This was followed by a sharp turn (if the participants wanted to, they could lead [walk] the bicycle through all sharp turns) before stopping within a square of 0.6 × 2 meters (with both feet and the bicycle within the square). Beyond this square was a 30-meter long cone-shaped marking, drawn on the asphalt. The participants' task was to cycle as straight as possible on a line in the middle of the cone-shaped marking (Task 2a: cycling straight and ringing the bell). Plastic cones were placed at 17, 21 and 25 meters, and participants were required to ring the bicycle's bell when they passed these. The straight line within the cone-shaped marking ended with another stop square of 0.6 × 2 meters. This was followed by a second sharp turn before a straight line crossed by five stop lines 5 meters apart. The participants' next task was to cycle as slowly as possible between the five stop lines and to put one foot down at every line (Task 3: cycling slowly). This task also ended with a stop square of 0.6 × 2 meters. This was followed by a third sharp turn that took the participants back to the line in the middle of the cone-shaped marking (Task 2b: cycling straight without ringing the bell) and ending at the last stop square. This time, however, the participants were requested not to ring the bicycle bell as they passed the three plastic cones. The participants' path through the test track thus formed a figure of eight shape. Each participant completed the test track cycling, all in all, 5 times (four laps each time).

3.5 Measurements

Two women's bicycles from Cresent were used; these were fitted with gyro sensors (Racelogic Inertial Measurement Unit, model IMU02; Racelogic Ltd, Buckingham, UK) in the bicycle baskets (on the handlebar). A VBOX 3i data logger (Racelogic Ltd) was placed in the bicycle bags on the right side (Figure 2 shows one of the instrumented bicycles).

The alcohol concentration in the exhaled breath was measured using the Breathalyzer Dräger 6820 (Drägerwerk, 2017), used by Swedish police. With a conversion ratio of 2100:1, no significant difference exists between breath alcohol concentration

Figure 2 One of the instrumented bicycles used in the experiment.

and blood alcohol content if the breathalyser is used according to the manufacturer's instructions (Jurič et al., 2018). At each assessment timepoint, the participants did two alcohol breath tests, after which we calculated an average value. A higher alcohol content reflects a higher alcohol concentration.

3.6 Design

The study design was a mixed 2 (experimental group versus control group) by 5 (assessment timepoints) analysis of variance (ANOVA), i.e. two independent variables. The dependent variables were stability (six measures for each bicycling task), speed and alcohol concentration level.

3.7 Statistical considerations

One of the participants in the experimental group was accidentally provided with alcohol before the first cycling session and his data from Time 0 (baseline) was therefore excluded from all analyses. Time 0 is thus based on data from 18 participants in the experimental group. For cycling stability measures, the number of participants varies further between different analyses because the gyro sensors did not always record data

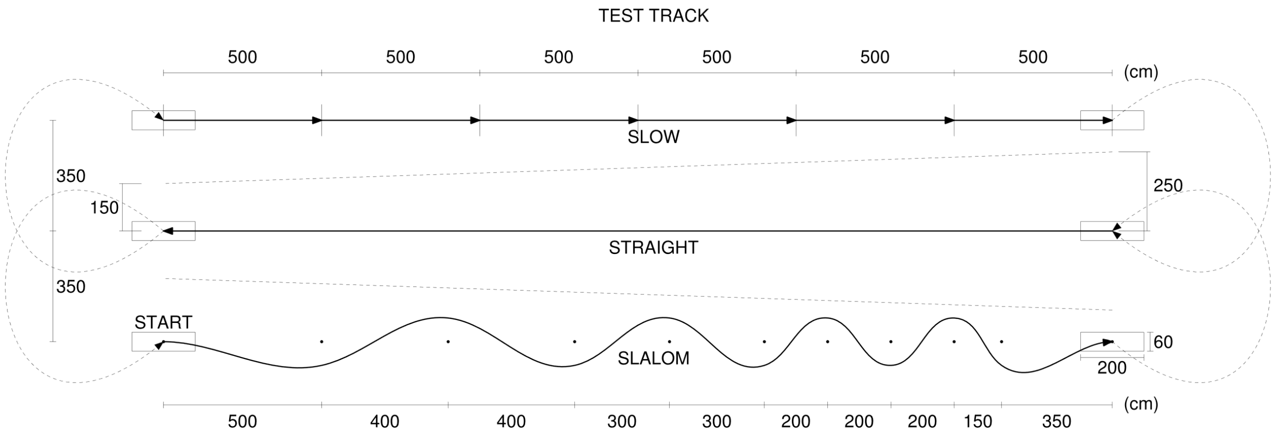


Figure 1 An illustration of the cycling track with the threetasks: slalom, straight and slow cycling (going from start and creating a figure of eight shape).

correctly. However, if a participant's value for a specific task at a specific Time session was not recorded properly, the mean value for the group was used to complete the statistical design (not more than once for a unique group and or condition). All analyses with the inclusion of unique values and all analyses without the inclusion were performed. The same effects were obtained, and the interpretations and conclusions were not affected.

There were 2 × 5 mixed ANOVAs with a between-participant variable (experimental group versus control group) and a within-participant variable (assessment Times 0–4). If a main effect or interaction effect was obtained, pairwise comparisons were performed. Corrections were carried out if the variance of a variable was significant (Mauchly's test of sphericity). In addition, the pairwise comparisons were carried out with a Bonferroni correction. There was a total of 24 analyses for the stability measures (6 for slalom, 6 for slow, and 12 for straight cycling – with or without bell ringing).

4 Results

4.1 Cycling stability

Figure 3 below demonstrates the data recordings for one Time session, for one unique participant. The three tasks were clearly identified (with two recordings for cycling straight) for each lap, with four laps for each Time session.

Example of data recordings from the VBOX data logger. The three tasks can be identified in the illustration (red = slalom, green = straight, and blue = slow).

To identify suitable cut-off values for the angular velocity measurements, the distribution curves were studied. Based on the distribution curves 3 different cut-off values were chosen (see Figure 4). As can be seen in Figure 4, the distributions varied both within and between tasks.

Dyroll rates for the three tasks: cycling slalom, straight, and slowly.

The number of measurement points for the respective cut-off value was then aggregated per participant, wherein a higher index indicated a more unstable cycling performance. For the lean angular velocity measurement (roll rate), the cut-off values were similar to those used in a previous study where the participants cycled on a treadmill (Andersson et al., 2023). The cut-off values for the steering angle (yaw rate) were significantly greater, which was expected as the test track was more demanding than cycling straight on a wide treadmill.Table 1 shows the cut-off values chosen for analysis of the angular velocity measurements for the different tasks on the test track.

4.2 Alcohol concentration

Both the experimental and the control group cycled the first session sober (0.00‰ alcohol level). Then, the participants in the experimental group were provided with alcohol in the form of vodka to achieve the target alcohol level values of 0.30‰, 0.75‰, and 1.00‰, and then to maintain an alcohol concentration level of 1.00‰. Figure 5 shows that the experimental group did not quite reach the target values, with the highest average alcohol level reached being 0.87‰ (6 participants >1.0‰; 10 participants <0.9‰). Despite

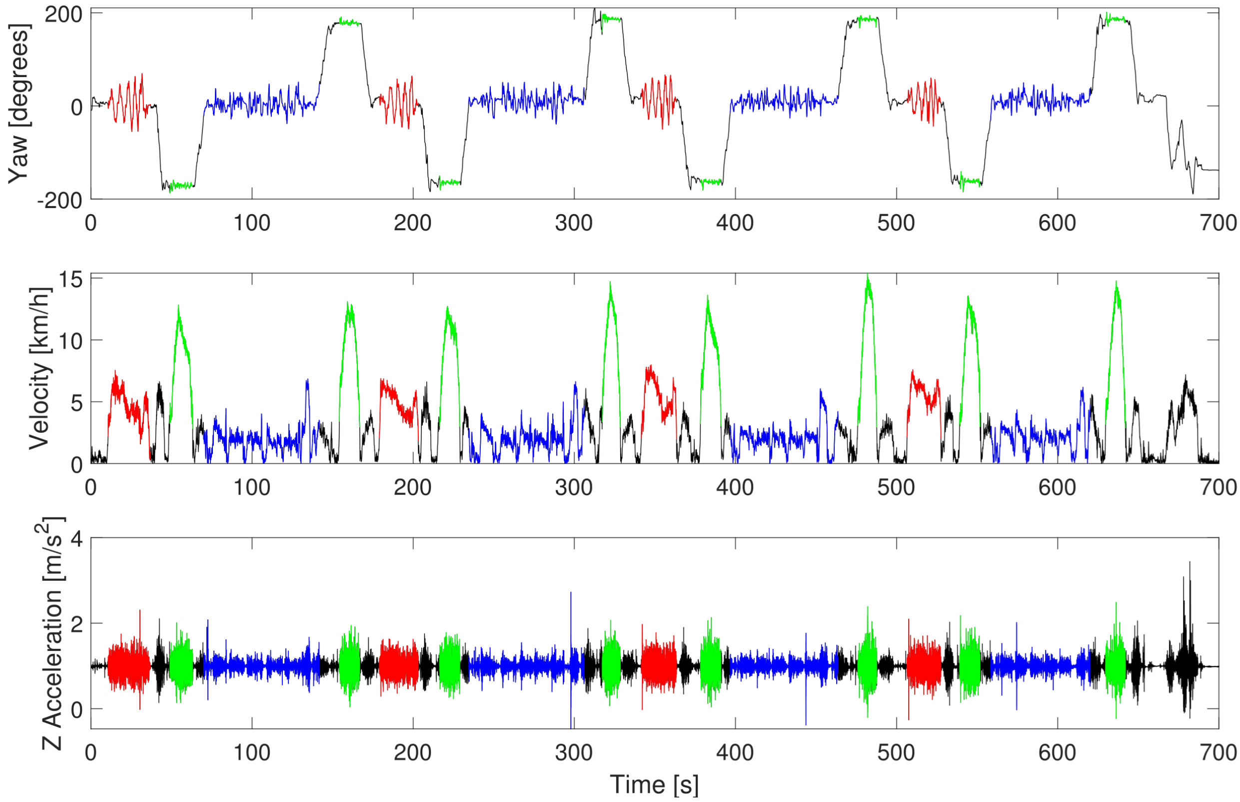


Figure 3 Example of data recordings from the VBOX datalogger. The three tasks can be identified in the illustration (red = slalom,green = straight, and blue = slow).

Table 1 Limit values for angular velocity measurements according to the task (cycling slalom, straight, and slowly).

	Slalom (°/s)			Straight (°/s)			Slowly (°/s)		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
Roll rate	5	10	15	5	10	15	5	10	15
Yaw rate	50	100	150	50	75	100	50	100	150

this, several of the participants were noticeably affected by the alcohol. One of the female participants was so affected that she vomited before cycling at Time 3 (when she had an average alcohol content of 0.61‰); she was therefore not provided with additional alcohol but was allowed to complete the experiment. The amount of alcohol needed to achieve the target values was calculated in the same way for all participants in the experimental group. Figure 5 shows that the alcohol concentration varied between the participants (e.g. range of 0.55‰–1.16‰ at Time 4). The total amount of alcohol consumed also varied widely between participants, ranging from 20 centilitres to 54 centilitres of vodka (with an alcohol content of 40‰).

4.3 Speed measures

When cycling speed was analysed (three 2 × 5 mixed ANOVAs), only one main effect was found for all three tasks studied. The speed increased (from 5.4 km/h to 5.9 km/h) over time in the slalom task $F(4, 44) = 2.71$, $p < 0.05$, $MSe = 0.08$) for both groups. For both the cycling straight and slowly tasks, no differences were found. The low degree of freedom was due to technical problems with the GPS signal. Thus, speed was not affected over time (except for the slalom task for both groups) and was therefore not a confounding variable. The experimental group did not cycle faster during the slow cycling task for instance, compared to the control group.

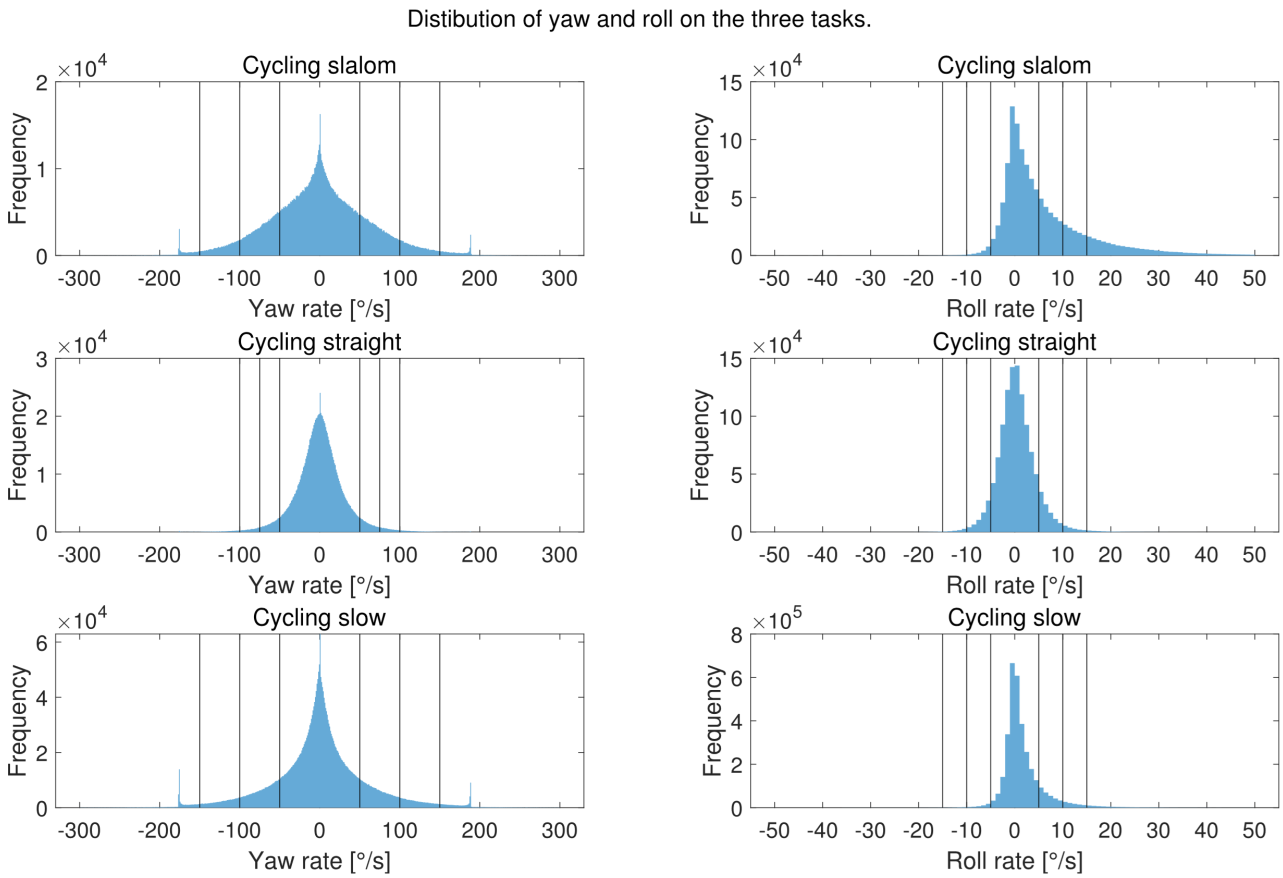
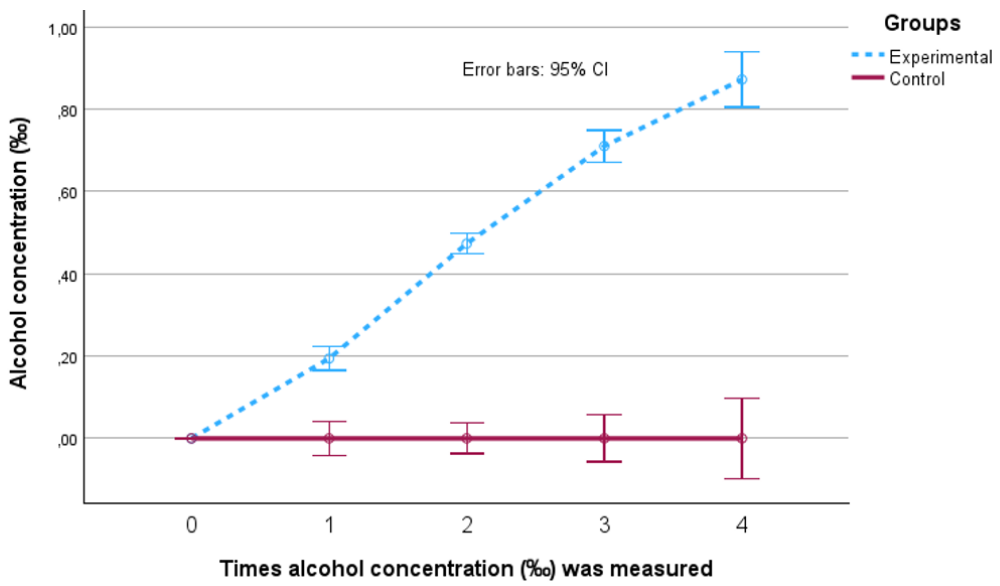


Figure 4 Distribution of yaw and roll rates for the threetasks: cycling slalom, straight, and slowly.



Average (‰)	0.00	0.19	0.47	0.71	0.87
Min	0.00	0.10	0.31	0.52	0.55
Max	0.00	0.43	0.60	0.84	1.16

Figure 5 Average, minimum and maximum alcohol concentration values (‰) for participants in the experimental and control groups at Times 0–4

4.4 Stability measures

All descriptive data for Times 0–4 for both groups are presented in Table 2. The different tasks were performed at different speeds. Cycling straight was completed in a higher speed (mean = 19.6 km/h) than cycling slowly (mean = 1.7 km/h) and slalom (mean = 4.7 km/h). The data presented in Table 2 represent the total mean values (sampling time) for each group for each specific session and task.

Twenty-four 2 × 5 mixed ANOVAs were computed (see Table 3). Although there were 3 tasks, and 3 levels of roll and yaw, suggesting 18 ANOVAs, cycling straight was divided into 2 separate variables—1 cycling straight and ringing the bell subtask and 1 cycling straight without ringing the bell subtask; thus, the number of ANOVAs increased from 18 to 24. Not all ANOVA findings are discussed. Instead, the results for one roll rate and one yaw rate for each task are presented, with figures, and following pairwise comparisons. All limit levels (1–3) are presented as well, but only for one for each task.

The sampling time value indicate how manys seconds a participant uses a roll rate over a specified threshold. The VBOX used 100 Hz and the first number in Table 2 is 1046.4, that indicate that Slalom Roll Rate 5°/s for the experimental group was over 5°/s = 10.46 seconds (sampling time).

4.5 Cycling slalom

Roll rate level 1 (>5°/s) and yaw rate level 1 (>50°/s) data are presented in Figure 6 and Figure 7. These figures are used to exemplify the pattern which is similar for all ANOVAs for cycling slalom. The participants' instability (roll rate >5°/s) at the various times was influenced by whether they were part of the experimental or the control group (interaction effect). Figure 6 shows that instability increased slightly in the experimental group, while it decreased in the control group. Pairwise comparisons showed that instability was significantly higher in the experimental group than in the control group at Times 3 and 4 (when the experimental group's average alcohol concentration was approximately 0.7‰ and 0.9‰, respectively).

The participants' instability (yaw rate >50°/s) at the various times was affected by whether they were part of the experimental or control group (interaction effect). Figure 7 shows that instability increased slightly in the experimental group, while it decreased in the control group. Pairwise comparisons showed that instability was significantly higher in the experimental group than in the control group at Times 3 and 4 (when the experimental group's average alcohol concentration value was approximately 0.7‰ and 0.9‰, respectively).

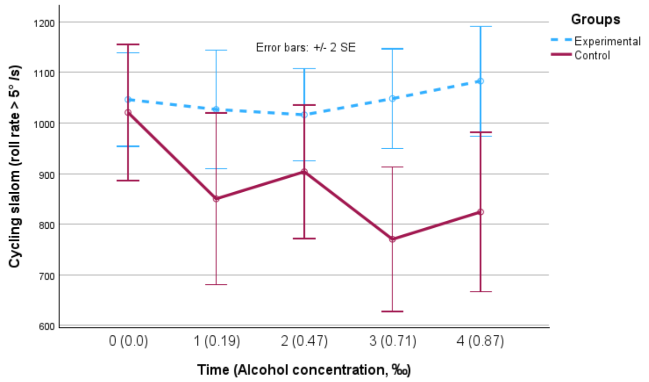


Figure 6 Experimental and control groups' change in instability (roll rate >5°/s) over time when cycling slalom

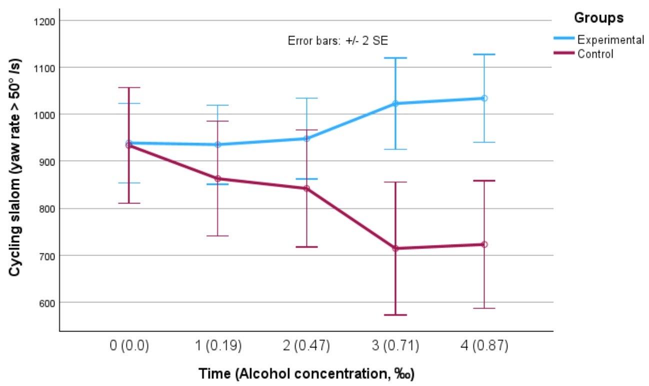


Figure 7 Experimental andcontrol groups' change in instability (yaw rate >50°/s) over time when cycling slalom

Table 2 Descriptive data (sampling time) for theexperimental and control groups, respectively, for Times 0–4, for three levelsof roll and yaw rate for the three tasks: cycling slalom, slowly and straight (withand without bell ringing).

	Group	Time 0		Time 1		Time 2		Time 3		Time 4	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Slalom Roll Rate											
5°/s	E	1046.4	233.4	1026.9	233.6	1016.3	220.3	1048.3	191.5	1082.9	212.2
	C	1020.9	96.1	850.3	297.3	903.9	134.9	770.4	257.3	824.3	282.6
10°/s	E	585.3	151.5	583.8	157.1	599.6	166.8	648.3	129.8	671.8	136.2
	C	573.1	134.3	509.4	165.8	498.1	157.4	431.3	195.0	474.1	216.3
15°/s	E	329.0	114.6	341.0	104.6	370.5	123.9	416.6	95.0	441.9	91.9
	C	348.3	176.6	315.5	182.9	314.2	152.1	274.2	178.6	309.2	190.7
Slalom Yaw Rate											
50°/s	E	938.9	212.8	935.4	207.0	948.0	213.5	1022.8	204.6	1034.0	184.0
	C	933.7	91.0	862.8	115.0	841.9	104.6	714.2	228.6	722.7	242.0
100°/s	E	241.2	56.9	244.5	69.4	274.2	88.7	324.4	86.4	338.2	64.1
	C	287.2	108.2	255.6	113.9	246.9	110.8	208.4	121.7	220.2	121.9
150°/s	E	53.8	27.5	57.1	25.0	67.4	33.0	91.0	38.3	93.7	25.4
	C	74.1	56.3	68.2	46.6	59.7	47.5	58.6	61.5	53.1	55.7
Slowly Roll Rate											
5°/s	E	716.1	489.4	787.1	481.0	1189.3	916.8	1492.5	819.9	1529.7	589.0
	C	719.1	325.7	728.7	372.0	657.0	323.5	617.1	274.9	673.0	287.0
10°/s	E	192.8	174.9	212.2	157.1	425.5	448.9	570.0	408.9	629.3	301.0
	C	176.4	131.9	163.4	128.3	152.8	134.1	134.8	115.9	144.3	100.0
15°/s	E	59.9	69.3	67.3	56.6	175.1	226.4	252.6	224.0	283.4	163.1
	C	63.5	67.0	47.4	45.3	53.3	55.7	40.6	45.4	38.8	28.9
Slowly Yaw Rate											
50°/s	E	1788.8	1140.8	1926.3	1068.0	2335.0	1285.5	2505.8	1151.4	2347.2	729.8
	C	1792.9	1114.6	1780.6	861.5	1770.2	730.0	1505.4	705.4	1552.1	703.0
100°/s	E	592.3	619.1	633.9	543.7	930.5	830.2	1061.2	760.9	895.8	426.5
	C	541.0	562.0	515.9	427.3	497.3	403.9	401.6	317.3	442.7	313.6
150°/s	E	193.3	275.6	207.9	223.6	385.8	507.5	475.7	470.0	331.7	215.3
	C	164.1	251.0	137.7	177.7	121.0	157.5	99.6	118.9	117.2	115.8
Straight Bell Roll Rate											
5°/s	E	154.9	77.1	155.7	77.3	162.5	79.9	186.2	78.2	202.5	86.7
	C	219.3	58.4	227.6	53.9	213.0	59.5	207.0	78.3	215.5	82.6
10°/s	E	18.1	19.5	18.1	19.9	20.4	20.1	30.0	25.3	39.9	36.9
	C	36.3	27.5	34.3	16.3	30.7	21.7	30.5	25.3	36.7	25.4

Continued on next page

Table 2 continued

	Group	Time 0		Time 1		Time 2		Time 3		Time 4	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
15°/s	E	3.7	5.4	4.1	5.5	2.9	3.2	8.1	8.8	11.6	14.7
	C	9.6	10.0	7.1	4.7	7.6	7.3	8.0	12.5	10.8	9.9
Straight Bell Yaw Rate											
50°/s	E	93.6	43.0	87.7	44.4	106.2	53.0	147.3	72.7	181.3	66.0
	C	107.7	33.5	85.8	30.0	86.4	32.0	81.0	42.2	83.9	37.8
75°/s	E	25.2	13.9	24.8	16.7	32.8	20.8	51.2	30.8	66.1	33.1
	C	36.2	22.0	30.3	15.5	26.6	18.1	25.0	13.0	32.2	16.1
100°/s	E	7.9	6.4	6.9	6.8	10.2	9.1	18.2	14.2	26.6	21.1
	C	13.5	9.6	10.1	5.3	8.9	8.9	7.6	5.4	10.2	7.0
Straight No Bell Roll Rate											
5°/s	E	156.3	78.0	159.2	73.8	173.7	78.5	192.9	73.7	206.3	77.7
	C	226.5	58.7	230.9	63.7	219.6	55.1	224.2	86.1	224.2	82.2
10°/s	E	19.4	21.5	19.4	18.4	24.7	23.2	31.4	28.8	42.9	30.9
	C	41.3	26.2	34.3	25.1	38.0	27.0	37.6	25.6	41.1	25.0
15°/s	E	3.6	5.9	3.6	4.4	5.0	6.3	9.0	10.7	14.1	12.7
	C	13.3	12.1	8.2	8.7	13.1	17.6	8.8	6.8	11.2	10.7
Straight No Bell Yaw Rate											
50°/s	E	86.9	45.1	84.1	42.8	112.5	57.9	155.3	89.8	188.4	61.4
	C	93.7	25.5	91.3	30.2	79.2	37.2	84.0	44.9	77.1	30.5
75°/s	E	26.6	20.0	27.4	18.5	38.6	22.5	59.0	36.1	73.8	29.4
	C	32.2	16.9	29.6	15.3	27.1	14.9	27.4	15.8	24.0	12.4
100°/s	E	8.3	9.5	11.5	9.5	13.6	11.4	23.7	18.8	30.0	16.3
	C	11.9	9.7	10.4	8.8	10.2	8.6	8.5	5.6	8.0	5.1

E = Experimental group (n = 19), C = Control group (n = 9)

4.6 Cycling straight

Roll rate level 3 (>15°/s) and yaw rate level 3 (>100°/s) data are presented in Figure 8 and Figure 9 (one with bell ringing and one without bell ringing). These figures are used to exemplify the pattern which is similar for all ANOVAs for cycling straight. The participants' instability (roll rate >15°/s) changed over time (main effect). The change was also influenced by whether participants were in the experimental or control group (interaction effect). Figure 8 shows that the instability increased in the experimental group, while it did not decrease in the control group. Pairwise comparisons showed significant effects at Time 4 only.

Participants' instability (yaw rate >100°/s) changed across time (main effect). However, the change was influenced by whether participants were in the experimental or control group (interaction effect). Figure 9 shows that instability increased in the experimental group, while it decreased slightly in the control group. Pairwise comparisons showed that instability was significantly higher in the experimental group than in the control group at Times 3 and 4 (when the experimental group's average alcohol concentration was approximately 0.7‰ and 0.9‰, respectively).

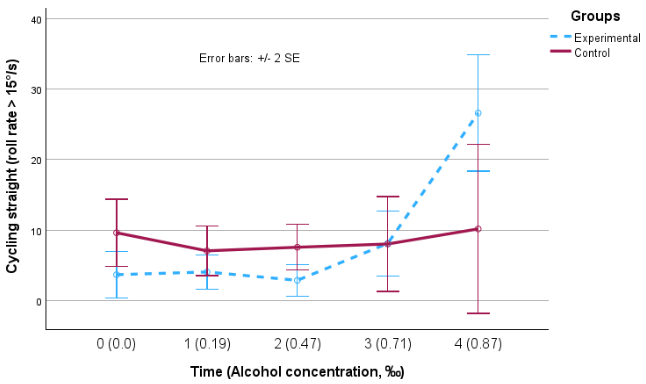


Figure 8 Experimental and control groups' change in instability (roll rate >15°/s) over time when cycling straight

4.7 Cycling slowly

Roll rate level 2 (>10°/s) and yaw rate level 2 (>100°/s) data are presented in Figure 10 and Figure 11. These figures are used to exemplify the pattern which is similar for all ANOVAs for cycling slowly. The participants' instability (roll rate >10°/s) changed over time (main effect) and between groups (main effect). The change was also influenced by whether they were participants in the experimental or control group (interaction effect). Figure 10 shows that instability

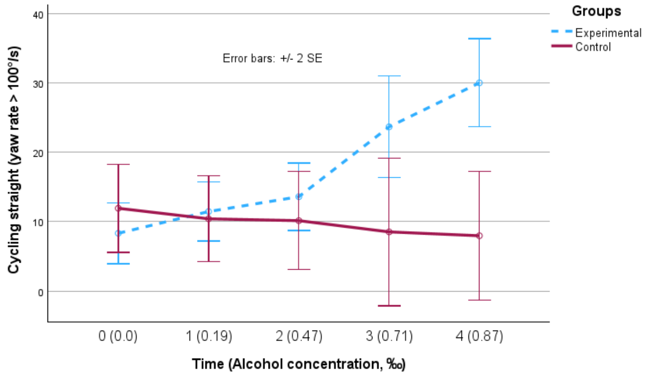


Figure 9 Experimental and control groups' change in instability (yaw rate >100°/s) over time when cycling straight

increased in the experimental group, while it decreased slightly in the control group. Pairwise comparisons show that instability was significantly higher in the experimental group than in the control group at Times 3 and 4 (when the experimental group's average alcohol content was approximately 0.7‰ and 0.9‰, respectively).

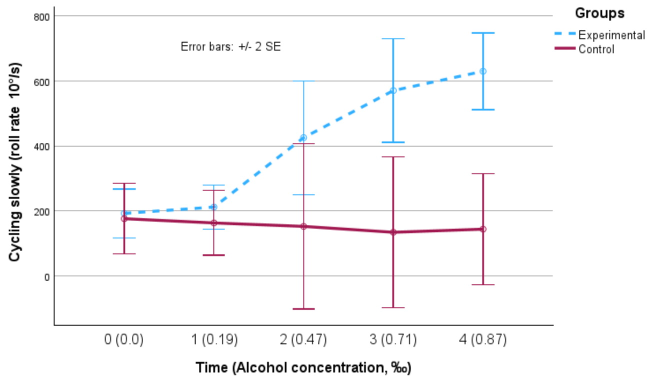


Figure 10 Experimental andcontrol groups' change in instability (roll rate >10 °/s) over time when cycling slowly

The participants' instability (yaw rate >100°/s) over time was affected by whether they were in the experimental or control group (interaction effect). Figure 11 shows that instability increased in the experimental group, while it decreased slightly in the control group while cycling slowly. Pairwise comparisons showed that instability was significantly higher in the experimental group than in the control group at Times 3 and 4 (when the experimental group's average alcohol concentration was approximately 0.7‰ and 0.9‰, respectively).

Table 3 Main and interaction effects for the 24 ANOVAs on the different stability measures

	Main effect of Group		Main effect of Time		Interaction effect of Group × Time		
	F(1,26)	MSe	F(4,104)	MSe	F(4,104)	MSe	partial eta squared
Slalom Roll Rate 5°/s	ns		ns		3.6**	18267	0.12
Slalom Roll Rate 10°/s	ns		ns		7.2**	6228	0.22
Slalom Roll Rate 15°/s	ns		ns		8.6***	3413	0.25
Slalom Yaw Rate 50°/s	ns		ns		10.6***	11400	0.29
Slalom Yaw Rate 100°/s	ns		ns		21.1***	1595	0.45
Slalom Yaw Rate 150°/s	ns		3.0*	282	15.2***	281	0.37
Slowly Roll Rate 5°/s	4.9*	1335517	6.6***	108500	10.0***	108500	0.28
Slowly Roll Rate 10°/s	7.7**	2049738	6.5***	32409	8.7***	32409	0.25
Slowly Roll Rate 15°/s	7.9*	54632	5.1**	10854	6.9***	10854	0.21
Slowly Yaw Rate 50°/s	ns		ns		4.6**	238435	0.15
Slowly Yaw Rate 100°/s	ns		ns		4.1**	96008	0.14
Slowly Yaw Rate 150°/s	ns		ns		3.3*	37447	0.11
Straight Bell Roll Rate 5°/s	ns		3.0*	659	6.3***	659	0.20
Straight Bell Roll Rate 10°/s	ns		3.8**	176	3.1*	176	0.11
Straight Bell Roll Rate 15°/s	ns		3.4***	78	ns		-
Straight Bell Yaw Rate 50°/s	ns		9.8***	786	16.7***	786	0.39
Straight Bell Yaw Rate 75°/s	ns		8.5***	224	10.5***	224	0.29
Straight Bell Yaw Rate 100°/s	ns		4.5**	83	6.4***	83	0.20
Straight No bell Roll Rate 5°/s	ns		5.7***	431	8.0***	431	0.23
Straight No bell Roll Rate 10°/s	ns		6.4***	124	4.0**	124	0.13
Straight No bell Roll Rate 15°/s	ns		3.4*	41	4.3**	41	0.14
Straight No bell Yaw Rate 50°/s	ns		9.6***	1011	15.9***	1011	0.38
Straight No bell Yaw Rate 75°/s	ns		7.5***	266	12.6***	266	0.33
Straight No bell Yaw Rate 100°/s	ns		3.6**	98	7.0***	98	0.21

ns = not significant, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

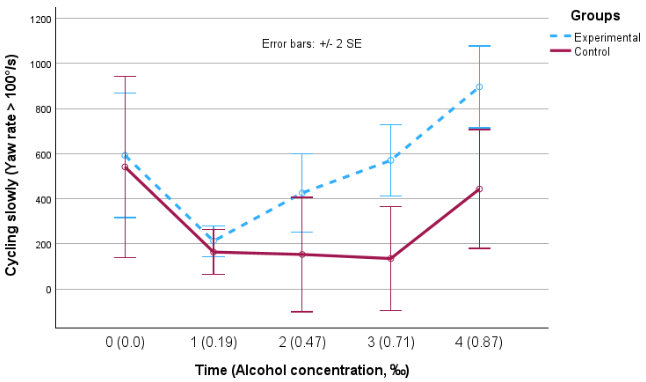


Figure 11 Experimental andcontrol groups' change in instability (yaw rate >100 °/s) over time when cycling slowly

5 Discussion

The present experiment aimed to develop a better understanding of cycling stability for different cycling tasks during alcohol intoxication. As increased alcohol concentration decreases stability (Modig et al., 2012), differences between the experimental group, with an increasing alcohol concentration, and the sober control group can indirectly be used to identify suitable measures for cycling stability.

The measure of cycling speed did not reveal any significant differences between the experimental and the control group and is therefore not a confounding factor for this experiment.

The distributions of roll and yaw rates show that roll rates of >5°/s, 10°/s and 15°/s were suitable for measuring instability for all cycling tasks studied. The roll rates were small in comparison to the yaw rates. The yaw rate distributions show higher suitable values, with rates of >50°/s, 100°/s and 150°/s appropriate for assessing instability when cycling slalom and slowly, and yaw rates of >50°/s, 75°/s and 100°/s suitable for cycling straight. It was reasonable and not surprising that cycling straight revealed lower yaw values. However, the relative impact of roll and yaw is still not clearly understood (Edelmann et al., 2015).

The next step was to analyse how different levels of roll and yaw rates can be used to detect instability. When cycling slalom, the results showed that yaw rate at level 3 (>150°/s) was the most sensitive in discriminating between stable and unstable performances (see Table 3), i.e. the largest effects were obtained for yaw rate at levels 2 and 3 (ηp 2 = 0.45 and 0.37, respectively). When cycling straight, the yaw rate at level 1 (>50°/s) was the most sensitive in discriminating between stable and unstable performances (ηp 2 = 0.39 and 0.38 [with and without bell ringing]). For cycling straight and slalom, yaw rate was the most sensitive; different levels were sufficient, and roll rate was also significantly affected (mean approximately. ηp 2 = 0.16). When cycling slow, roll rates were adequate at all angular rate levels (mean approximately ηp 2 = 0.25) in discriminating between stable and unstable performance (see Table 3). These findings suggest, firstly, that the importance of yaw and roll variables depends on the tasks being performed by the cyclist. Second, examination of only the higher angular rates is not sufficient (Andersson et al., 2023). Regarding roll rates, all levels worked well when cycling slow. In contrast, low yaw levels worked best when cycling straight, while high yaw levels worked best for cycling slalom. Cycling speed (and the speed increase for both groups on the slalom task) was stable for both groups, and seems not to have affected the results, even if speed is related to stability (Cain et al., 2016).

The effects of alcohol blood concentration and crashes are clear in the literature (De Waard et al., 2016). In addition, instability increases as an effect of alcohol blood concentration (Andersson et al., 2023). The relation between instability (as measured here) and crash involvement is not yet supported empirically, but the relation between alcohol intoxication and crashes suggests it is reasonable to assume that instability is one of the causes. When participants reached alcohol concentration values of 0.7‰, it was statistically obvious that participants were less stable compared to the control group, as in earlier findings (Andersson et al., 2023). It was also a trend of stability improvement over time for controls. As in Andersson et al. (2023), we interpret this as a learning effect. Sober controls became a little bit better at performing the three tasks.

Hence, we are closer to the long-term objective, which is to measure cycling stability in a valid way when cyclists perform different tasks, in order to develop an ARAS for cyclists. Several complexities need to be overcome before this objective is fulfilled. First, an intoxicated cyclist will produce false alarms continuously. This instability is mostly of benefit to the intoxicated cyclist and no other cyclists. Instability due to infrastructure problems (slippery road surface etc.), on the other hand, is more relevant for all, and should be distributed to all cyclists. The ARAS developed needs to be sophisticated. Second, the validity associated with the pragmatics of developing an ARAS is, as stated above, not addressed here. It is uncertain whether the existence of an ARAS with this sophisticated functionality would in fact reduce crashes related to instability; this is an empirical question for future research. The results obtained here suggest the need for a high degree of smart technology in the ARAS, to warn the relevant cyclist(s), but not provide cyclists with irrelevant information (false alarms).

As with all studies, this one has its limitations. The tasks were performed in a controlled environment (i.e. on a test track in a disused parking place) and not in real traffic. The track was dry and had no slippery surface. In order to validate the suggested measures for cycling stability, further research is needed in conditions simulating real traffic. Other limitations are the relatively small sample size and the homogeneity of the participants; all were young, healthy and had similar cycling experience. It is not clear how valid these results will be for children, older adults, and novice cyclists for example, and this requires further examination.

6 Conclusions

Assuming there is a strong relationship between alcohol concentration and cycling stability, we were able to identify three measures sensitive in discriminating between stable and unstable cycling performance. These measures were yaw rate at level 3 (>150°/s) when cycling slalom, yaw rate at level 1 (>50°/s) when cycling straight and roll rates at levels 1–3 (>5°/s, 10°/s, and 15°/s) when cycling slowly. Some useful steps towards the development of an ARAS with instability warnings have thus been taken.

CRediT contribution statement

Jan Andersson: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Writing—original draft. **Henriette Wallén Warner:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing—original draft. **Peter Andrén:** Data curation, Writing—original draft.

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Ethics statement

The project was reviewed and supported by the National ethical research board (EPN: Dnr 2022-00159-01).

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