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Characteristic Rider Reactions to Autonomous Emergency Braking Maneuvers on Motorcycles

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Abstract

To be able to use autonomous emergency braking systems for motorcycles in a safe way, it is necessary to anticipate the reaction of riders to automatic braking maneuvers. Elsewise, an unintended reaction could inhibit the rider from being able to stabilize the vehicle or even cause destabilization (even through to a fall). It is therefore important to design automatic braking interventions in such a way that the rider's reaction stays within appropriate limits.

In previous studies, measures allowing the evaluation of the rider's adaptation to the changing vehicle state during a braking maneuver have been identified. In particular, head and upper body movement as well as the supporting force on the handlebars proved to be promising indicators. The reproducibility of the measured reactions for repetitions of a certain maneuver with the same rider could be proved [1].

In the studies described here, different maneuvers were repeated in a participant study with 14 riders in order to evaluate the reproducibility across riders. Both, automatic braking maneuvers and braking maneuvers operated by the rider him/herself were performed. Obviously, riders show significant differences in their behavior when braking themselves, whereas the upper body movements - as an involuntary reaction to the unexpected braking maneuver - are very homogeneous during automatic braking maneuvers.

The results of the study show that the pitch movement of the rider's upper body alone can be used to determine whether the rider has reached a state in which he/she can control a maximum automatic deceleration. Furthermore, the results indicate that the physical reactions of unprepared riders to braking interventions show a high degree of homogeneity. This knowledge creates confidence that the evaluation of the controllability of automatic braking interventions in studies with relatively small numbers of participants can be transferred to a large number of riders.

13. Internationale Motorradkonferenz

Charakteristische Fahrerreaktionen auf automatische Notbremsmanöver auf dem Motorrad

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Zusammenfassung

Um automatische Notbremssysteme für Motorräder risikoarm einsetzen zu können, ist es notwendig, die Reaktion der Fahrer auf automatische Bremsmanöver einschätzen zu können. Das liegt darin begründet, dass der Fahrer durch eine ungewollte Reaktion sein Fahrzeug nicht mehr stabilisieren, oder es sogar (bis hin zum Sturz) destabilisieren könnte. Es gilt also, automatische Bremseingriffe so zu gestalten, dass die Fahrerreaktion sich in geeigneten Grenzen bewegt.

In vorangegangenen Studien wurden Maße identifiziert, mit denen sich die Anpassung des Fahrers an den sich ändernden Fahrzeugzustand während eines Bremsmanövers bewerten lassen. Hierbei erwiesen sich insbesondere Kopf- und Oberkörperbewegung sowie die Abstützkraft am Lenker als vielversprechend. Die Reproduzierbarkeit der gemessenen Reaktionen für Wiederholungen des Manövers mit dem gleichen Fahrer konnte nachgewiesen werden [1].

In den hier beschriebenen Untersuchungen wurden verschiedene Manöver im Rahmen einer Probandenstudie mit 14 Fahrerinnen und Fahrern wiederholt, um auch die fahrerübergreifende Reproduzierbarkeit zu evaluieren. Es wurden sowohl automatische als auch vom Fahrer selbst betätigte Bremsmanöver durchgeführt. Dabei wird deutlich, dass Fahrer bei selbst durchgeführten Bremsungen deutliche Unterschiede im Verhalten zeigen, während die Oberkörperbewegungen – als unwillkürliche Reaktion auf das für den Fahrer unvorhergesehene Bremsmanöver – bei automatischen Bremsmanövern sehr homogen ausfallen.

Die Ergebnisse der Studie zeigen, dass die Nickbewegung des Fahreroberkörpers alleine herangezogen werden kann, um zu ermitteln, ob der Fahrer einen Zustand erreicht hat, in dem er eine maximale automatische Verzögerung kontrollieren kann. Darüber hinaus deuten die Ergebnisse darauf hin, dass die körperlichen Reaktionen unvorbereiteter Fahrer auf einen Bremseingriff eine hohe Homogenität aufweisen. Dieses Wissen schafft Vertrauen, dass die Evaluation der Kontrollierbarkeit von automatischen Bremseingriffen in Studien mit verhältnismäßig kleinen Probandenstichproben auf eine große Anzahl an Fahrern übertragbar ist.

1 Introduction

The basis to design autonomous emergency braking systems (AEB) for motorcycles that can be used at al low risk is the knowledge on how riders react to unforeseen braking interventions of their vehicle. This knowledge is necessary to avoid rider reactions that can destabilize the rider-vehicle system. The autonomous braking intervention needs to be controllable for an unprepared rider. Maximum decelerations can only be applied, when the rider is in a ready-for-braking state. To reduce kinetic energy already in the phase before the ready-for-braking state is achieved, automatic braking interventions have to be designed in such a way that the rider's reaction stays within appropriate limits.

During a braking maneuver, the rider has to support inertial forces to control the forward movement of the body relative to the motorcycle. To stop this forward movement, the rider builds up body tension and supports the upper body against the handlebar. The faster the rider reacts to the changing state of the motorcycle, the faster the deceleration of the AEB can be maximized. When riders brake their motorcycle themselves, parts of the body tension and supporting force on the handlebar can be built up even in preparation to the deceleration, whereas in an automatic braking maneuver it is always a reaction to a surprising intervention.

In previous studies the limits for feasible decelerations in the phase before being 'ready-for-braking' have been identified [2], [3]. These limits represent a conservative estimation that is controllable for a large number of riders, including novice or untrained riders. To achieve a better understanding on how riders adapt to the changing vehicle state during a braking maneuver, a further study addressed the identification and evaluation of appropriate measures [1]. The identified measures focus on the relative movement between the rider's upper body and the motorcycle.

In the studies described in this paper, the previously identified measures were used to analyze the reproducibility of the rider behavior during braking maneuvers, including a comparison of automatic braking interventions vs. maneuvers in which the riders applied the brakes themselves. The aim of the experiments is to identify the most suitable measure to evaluate if the ready-for-braking state is already achieved.

2 Methods

In order to measure natural rider reactions, the participants shall not expect the autonomous braking maneuver as otherwise they could possibly prepare for it and this would distort the results. Therefore, they are not informed about the AEB testing before they experience the first automatic braking intervention.

Although, the emergency braking during the experiments is supposed to be unexpected, it should not express the character of a false positive braking intervention. Therefore, it is necessary to create a situation that presents a realistic true positive emergency braking scenario to the rider, like a suddenly decelerating target vehicle[1].

In the test scenario, the riders had to follow the preceding vehicle at a given velocity (70 km/h) at a certain distance (time headway 1.5 s). The emergency braking situation was caused by a sudden deceleration of the target vehicle. In order to avoid the risk of collisions between the motorcycle and

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[1] Paragraph adopted from [3].

the target vehicle, the dummy target EVITA (Experimental Vehicle for Unexpected Target Approach) was used. The dummy target, other test equipment and the experiments are described in the following sections.

2.1. Test equipment

Test Motorcycle[2]

The motorcycle used for the experiments is equipped with an inertial measurement unit (IMU) to record translational accelerations and rotational velocities, a GPS receiver to track the vehicle, and pressure sensors to monitor the actuation of the brakes. These measurements are used to determine the vehicle state.

For decelerating the motorcycle without an intervention of the rider, an actuator is mounted to the vehicle operating the foot brake. The test vehicle is equipped with a combined brake system. This means that by operating the foot brake, brake pressure is not only built up at the rear wheel, but also at the front. With this setup, it is possible to apply much higher automatic decelerations (up to 7 m/s^2) than by only applying the rear brake. The brake actuator can be activated via remote control.

To evaluate the rider state, additional measurement technique is installed. During the experiment, the rider is equipped with three motion tracking sensors that analyze the upper body and head movements. These sensors measure the translational accelerations in three axes and they contain 3-axes-gyroscopes. Two of the motion trackers are mounted on the rider's back, one at the level of the shoulder blades and one at the level of the lumbar spine. The third motion tracker is mounted at the top of the rider's helmet. The positions of the sensors are shown in Figure 1. Furthermore, to monitor the rider inputs, forces on the handlebar as well as brake actuation, clutch actuation and throttle are also recorded.

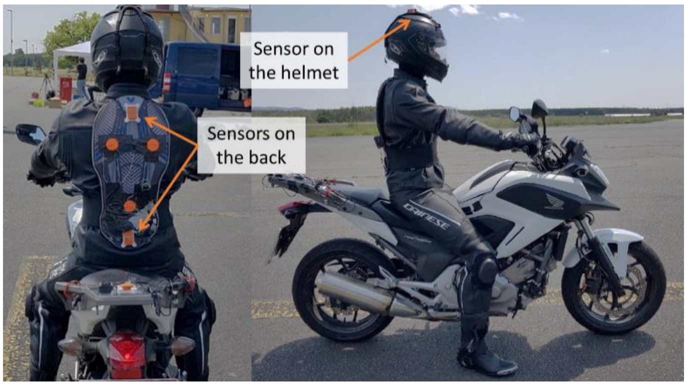

Figure 1: Sensor Positions

EVITA[3]

The EVITA test tool was developed to allow collision free investigation of anti-collision systems [4]. The dummy target consists of a towing vehicle and a trailer with a vehicle rear. The trailer can be decelerated independently from the front vehicle to simulate a rear-end collision situation. If the time-

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[2] Adopted from [1].

[3] Adopted from [3].

to-collision (TTC) between the following vehicle and the dummy target gets too short, the trailer is pulled forward to avoid a collision. The system is shown in Figure 2.

Figure 2: EVITA Dummy Target

2.2. Experiments

In order to analyze the characteristic rider reactions during autonomous emergency braking interventions, the participants experienced automatic braking interventions, as well as situations in which they had to apply the brakes themselves. The experiments were carried out successfully with 12 test persons.

For the automatic braking maneuvers, the desired brake pressure is built up with the maximum gradient defined by the system. Automatic decelerations of about 5 m/s^2 were implemented for the experiments. This level has been determined to be still controllable for unprepared riders in [5]. The related brake pressures were built up within 200 ms. An exemplary diagram is shown in Figure 3.

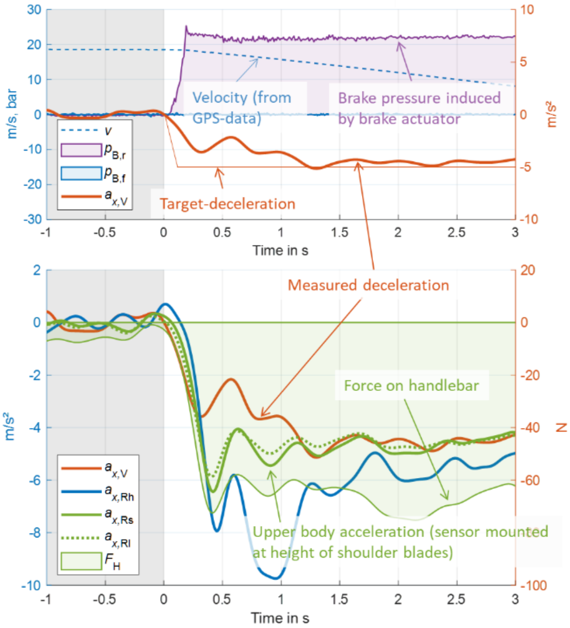

Figure 3: Exemplary diagram of an autonomous braking maneuver

The upper half of the diagram describes the vehicle state. It shows the GPS velocity *v* of the vehicle, the target deceleration as well as the longitudinal deceleration measured with the vehicle IMU $a_{x,\mathrm{V}}$. The diagram also contains the brake pressures at the rear brake cylinder $p_{\mathrm{B,r}}$ (where the automatic braking is initiated) and the front brake cylinder $p_{\mathrm{B,f}}$ (in case the rider additionally applies the hand brake lever)[4].The lower diagram shows the rider behavior. It contains the longitudinal decelerations at different points of the rider's upper body (head $a_{x,\mathrm{Rh}}$, shoulder level $a_{x,\mathrm{Rs}}$, lumbar spine level $a_{x,\mathrm{Rl}}$) as well as the force on the handlebar F_H. The vehicle deceleration $a_{x,\mathrm{V}}$ is added as a reference.

During a braking maneuver, the deceleration of the vehicle causes a forward displacement of the rider's upper body relatively to the vehicle. Only when the rider adapts to the changing vehicle state, the deceleration can also be found at the upper body. This causes a certain time lag between the vehicle deceleration and the deceleration of the rider body. This reaction time varies from rider to rider and is subject to the evaluations described in this paper. The aim is to find the most suitable measure to identify the reaction time and thus find the point at which the rider is ready to control maximum automatic deceleration.

3 Results

As described before, when the rider experiences an automatic braking intervention, due to inertial forces, the upper body moves forward. As the rider is connected to the motorcycle at the seat and the forward movement is limited by the tank, this results in a pitch movement that can be measured at different points of the upper body and also at the head of the rider. We assume that the point at which the rider starts to work against the forward movement is represented by the maximum of the pitch rate. From this point the pitch is slowed down until the rider pushes him/herself back to the initial position (→ negative pitch rate).

In experiments in [1] the head movement appeared to be the most promising measurement to evaluate the rider adaption to the decelerating motorcycle. This assumption was based on the fact that the head movement allowed the best differentiation between different maneuvers (autonomous braking vs. manual braking, see Figure 4). This analysis was limited by the fact that it was based on data from only one rider.

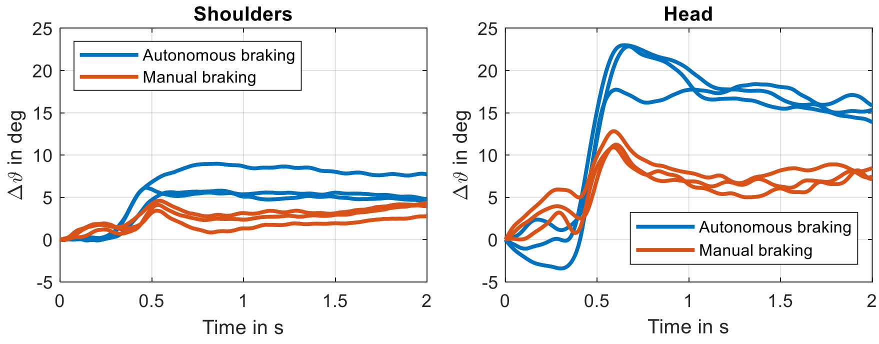

Figure 4: Pitch movement during braking maneuvers: Shoulder vs. Head [1]

Assessing the data from the experiments described here, it turns out that comparing different riders, the reaction to an automatic braking intervention is very homogenous for the upper body (measured at the shoulder and lumbar spine level), whereas the head movement can differ significantly (see Figure 5).

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[4] During the automatic braking maneuver, the pressure at the rear brake cylinder still causes pressure at one brake caliper at the front brake (combined brake system), to achieve sufficient deceleration. The caliper brake pressures are not shown in the diagram, in order to keep the clarity.

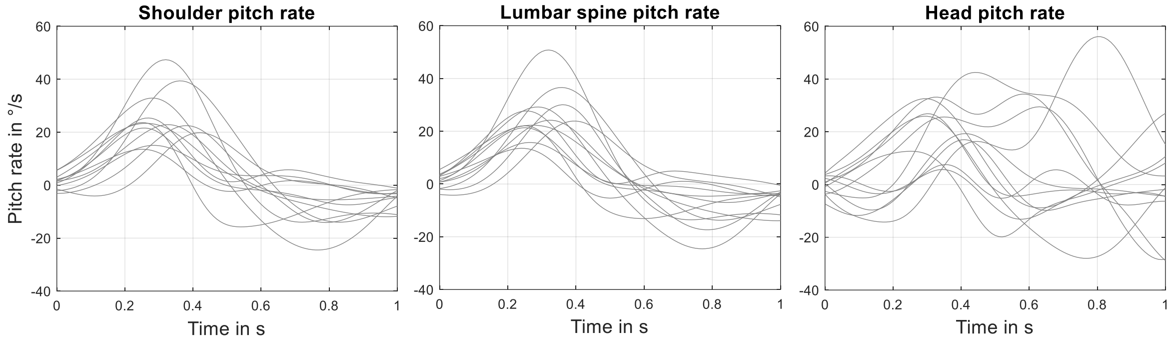

Figure 5: Body pitch rates for all participants after the beginning of the brake pressure increase in the AEB maneuvers[5]

The maximum of the pitch rate (rider starts counteracting the forward movement) was analyzed for shoulder, lumbar spine level and head for all 12 riders. For the analysis, the time at which the maximum is reached is particularly interesting. The absolute values are subject to a lot of influencing factors (e.g. body measurements of the rider), so they are barely comparable. Time $t = 0$ represents the beginning of the brake pressure increase.

As Figure 5 shows, the pitch rates at the shoulder and lumbar spine level follow a characteristic behavior, while the head movement can differ. This can be explained by the fact that the cervical spine is the most flexible part of the spine and the rider might for example raise or lower the head during the maneuver to get a better overview of the situation. Figure 6 shows examples for a rider whose head movement goes closely with the back (left diagram) during an automatic braking intervention and a rider whose head moves quite independently from the rest of the upper body (right diagram).

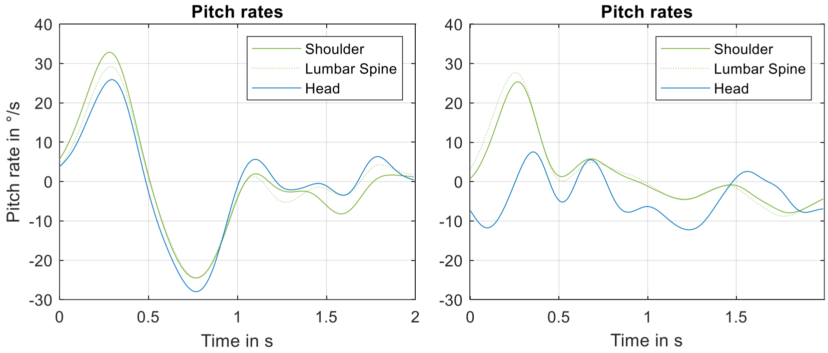

Figure 6: Body pitch rates of two different riders in AEB maneuvers

This partially occurring difference between the back and the head movement can also be found by comparing the time of the maximum pitch rate over all 12 riders. While the mean time of the maximum pitch rate is still very close for shoulder, lumbar spine and head, the standard deviation is significantly higher for the head. It is about twice as high as for shoulder and lumbar spine (see Table 1).

Table 1: Mean time for maximum pitch rate over all riders in the AEB maneuvers

	Mean time of max. pitch rate & std. dev. in s		**Min. time** of max. pitch rate in s	**Max. time** of max. pitch rate in s
Shoulder	0.32	0.06	0.26	0.43
Lumbar spine	0.31	0.05	0.25	0.41
Head	0.33	0.12	0.02	0.46

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[5] All data shown here are filtered with a Butterworth lowpass IIR filter, 2nd order, cutoff frequency 2 Hz.

The rider does not only counteract the relative forward movement and the pitch movement of the upper body by building up muscle tension in the torso. A not negligible part of the inertial forces is supported through the arms to the handlebar. This force was also measured during the experiments. Again, the informative value of the absolute values of the force rate is quite limited, e.g., due to the fact, that body proportions and body masses of the participants differ. Furthermore, because of different body postures, the force is applied to the handlebar in different angles, but only the force component perpendicular to the steering axis is measured. Due to these limitations, again, the time of the force rate maximum is evaluated.

As Figure 7 (left) shows, the qualitative course of the force rate curve is quite similar to the one of the upper body pitch rates. Comparing them directly (Figure 7, right), it turns out that the maximum of the force rate is reached slightly earlier than the maximum of the pitch rate. This does not only apply for the mean values (see Table 2) but also for each single rider. The maximum of the force rate is always reached before the maximum shoulder pitch rate. The time gap shows a mean value of 98 ms (min. 20 ms, max. 230 ms). This observation indicates that the support against the handlebar is required to counteract the pitch movement of the upper body. Due to the upper body acting as a long lever, it is not sufficient to support the movement against the vehicle via seat/tank by building up body tension.

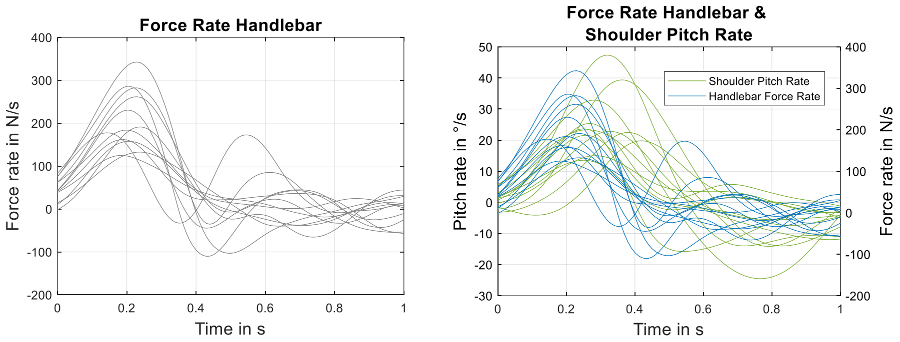

Figure 7: Handlebar force rates for all participants after the beginning of the brake pressure increase in the AEB maneuvers

Table 2: Mean time for maximum shoulder pitch rate/handlebar force rate over all riders in the AEB maneuvers

	Mean time of maximum & std. dev. in s		**Min. time** of maximum in s	**Max. time** of maximum in s
Shoulder pitch rate	0.32	0.06	0.26	0.43
Force rate handlebar	0.22	0.03	0.15	0.25

The homogeneity of the upper body movements in autonomous braking maneuvers cannot be retrieved in the maneuvers in which the riders had to apply the brakes themselves. In these cases, the pitch rate curves differ a lot between the riders. This can be explained by the fact that in the manual maneuvers, the deceleration profiles vary significantly. For example, some riders build up brake pressure very fast as soon as they notice the deceleration of the target vehicle and then slowly release the brakes again, while others apply the brakes smoothly and observe the situation and increase the deceleration when they get quite close to the target vehicle. Furthermore, the body movement is not a pure reaction to the changing vehicle state anymore. The rider initiates the deceleration consciously and thus can prepare for it, e.g. by building up body tension prior to applying the brakes. Some riders even show a negative pitch rate while applying the brakes, i.e. they straighten up during the maneuver. The diagrams in Figure 8 show the body movements for all participants in the manual braking maneuvers.

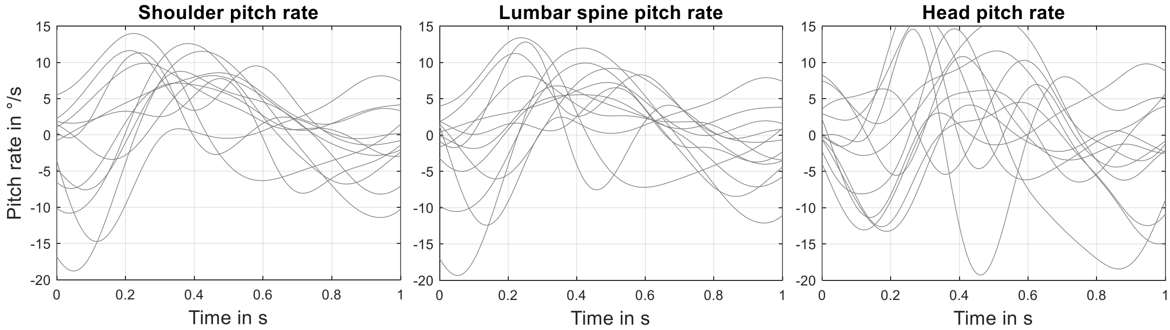

Figure 8: Body pitch rates for all participants in the manual braking maneuvers

The observations regarding the manual braking maneuvers allow the conclusion that the automatic braking interventions help to make the rider reaction ‘controllable’ or at least predictable. By provoking an unintentional rider reaction, influences of rider individual (conscious) behavior are interrupted and a characteristic process is initiated.

4 Conclusions

The experiments show that while the rider behavior in rider-induced braking maneuvers is quite inhomogeneous, the unintentional reactions to automatic braking interventions follow a certain pattern. This creates confidence that it is possible to estimate rider reactions when designing automatic braking interventions and to use this knowledge to develop autonomous emergency braking systems that can be used at low risk.

While the head movement appeared promising in former investigations as it showed the most significant differentiation between different maneuvers for one individual rider [1], the experiments described in this paper show that this measure shows a clear weakness in terms of reliability and reproducibility when comparing various riders. Thus, the head movement cannot be seen as a liable measure to evaluate if a rider has achieved the ‘ready-for-braking’ state.

It has been shown that the pitch movement of the rider’s upper body is a more reproducible measure to describe the rider reaction during automatic braking interventions. This measure stays within a slim corridor for all evaluated maneuvers. Due to the low flexibility of the spine between the lumbar spine level and the shoulder level, the pitch rates at both measuring points stay very close. For future studies this creates confidence that one single pitch rate sensor at the back might be sufficient.

An alternative measure to the pitch of the upper body is the force rate when the rider supports the movement against the handlebar. The force rate turned out to be similarly reproducible as the pitch rate. As the support against the handlebar seems to be required for counteracting the pitch of the upper body, the maximum occurs slightly earlier. Applying a force sensor to the handlebar could thus be an alternative to the pitch rate sensor at the rider’s back. While the pitch rate sensor gives the more conservative estimation on if the rider is ready for maximum deceleration (maximum pitch rate occurring later than maximum force rate), the advantage of the force rate evaluation is that the sensor is directly mounted to the vehicle and thus can be integrated to an AEB system more easily.

An additional conclusion of the study is that the homogeneity of the rider reactions in autonomous braking scenarios is quite promising regarding the possibility to evaluate the controllability of motorcycle AEB systems in studies with relatively small numbers of participants and to transfer the results to a large number of riders.

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Ethical approval

Ethical approval for the test track studies was obtained from the Ethics Commission of Technische Universität Darmstadt under reference *EK 39/2019*.

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