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Measures for the Evaluation of Riders' Adaption to the Changing Vehicle State during Autonomous Emergency Braking Maneuvers on Motorcycles

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ABSTRACT

For autonomous emergency braking maneuvers on motorcycles, not only physical limits have to be taken into account. In order to avoid rider reactions that can destabilize the rider-vehicle system, it has to be ensured that an autonomous braking intervention is controllable for the rider. Only when the rider is in a ready-for-braking state, a maximum deceleration can be applied.

In former research, e.g. [1] it has been shown, that small decelerations (up to 0.35 *g*) are in terms of rider stability feasible for unprepared riders. In previous studies at our Institute [2], [3] we identified limits of maximum decelerations that can be applied even before the rider reaches the ready-for-braking-state. These limits represent a conservative estimation that is controllable for all riders, including novice or untrained riders. This leads to the fact that safety potential gets lost for better-trained riders who could control higher decelerations. The performance of autonomous emergency braking systems for motorcycles can be increased in terms of effectiveness by further analyzing how good the rider is connected to his vehicle (body tension, hands on handlebar etc.) and the rider's capability to adapt to a changing vehicle state.

The work described in this paper identifies and evaluates measures for the adaption of the rider to changes of the vehicle state. These measures allow to rate the quality of the connection between rider and vehicle. The authors expect that the higher the quality of the rider-vehicle-connection is, the higher autonomous deceleration can be.

The main focus to evaluate the adaption to changes in the vehicle state lays on the relative movement between the rider's upper body and the motorcycle. This is expressed by the delay between the vehicle deceleration and the deceleration measured at the upper body of the rider. Experiments show that when a rider brakes by his own, there is nearly no time lag between the two deceleration signals, while the delay increases when the brakes are applied via remote control. The left diagram in figure 1 shows the vehicle acceleration ($a_{x,\mathrm{V}}$) and rider upper body acceleration ($a_{x,\mathrm{R}}$) for a braking maneuver that is performed by the rider himself. The same accelerations for an autonomous emergency braking maneuver are shown in the right diagram. The diagrams show that in a braking maneuver performed by the rider, the upper body movement follows the vehicle deceleration in a much more direct way than it does on an autonomously braking motorcycle. When braking himself, the rider is prepared to the deceleration and can build up body tension in advance. In case of an autonomous maneuver, the body tension follows the (unexpected) deceleration with a certain time lag.

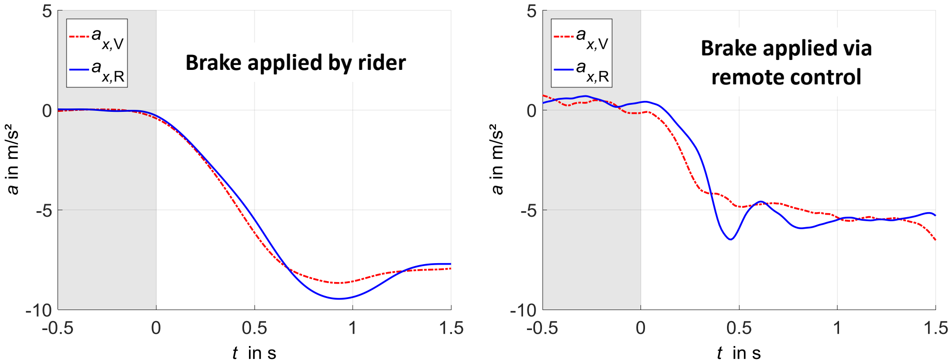


Figure 1. Comparison of the relative movement between the rider and the vehicle: Brake applied by the rider vs. brake applied via remote control.

Besides the time lag between the vehicle and rider deceleration, additional measures, such as the pitch movement of the rider's upper body and the force on the handlebar that the rider needs to push himself back (i.e., bringing the upper body back to its 'neutral' position) are discussed. The discussions include an evaluation of the significance and liability of the different characteristic values.

The discussed measures can be used not only to define when the rider is ready to bear a 'full' autonomous emergency braking but also to optimize the deceleration before reaching the ready-for-braking state to the rider's capabilities in order to obtain maximum effectiveness of the intervention.

Keywords: motorcycle autonomous emergency braking, MAEB, controllability, rider state, rider behavior

1 INTRODUCTION

In order to control the vehicle during a braking maneuver a motorcycle rider needs to support the inertial forces acting on his body. While in a passenger car the safety belt holds the driver back in his seat, on the motorcycle, the rider can only preserve his position on the vehicle by building up body tension and supporting the body movement against the handle bar.

If the rider brakes the motorcycle himself, he can prepare for the maneuver by building up these supporting forces in advance. In case of an autonomous braking maneuver, the supporting forces occur as a reaction to the increasing deceleration. The work described in this paper is based on the assumption that the faster this reaction to the increasing deceleration is, the earlier a maximum deceleration can be reached in order to maximize the effectiveness of the autonomous braking maneuver.

2 METHODS

In order to evaluate different measures for the rider's adaption to the vehicle state, autonomous braking maneuvers are compared with maneuvers in which the rider brakes himself. The test equipment and the experiments are described in the following sections:

2.1 Test equipment

The motorcycle used for the experiments is equipped with an inertial measurement unit (IMU) to record translational accelerations and rotational velocities, a GPS antenna 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, a brake actuator is mounted to the vehicle. This actuator operates 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 is 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 2.

Furthermore, to monitor the rider inputs, forces on the handlebar as well as brake actuation, clutch actuation and throttle are also recorded.

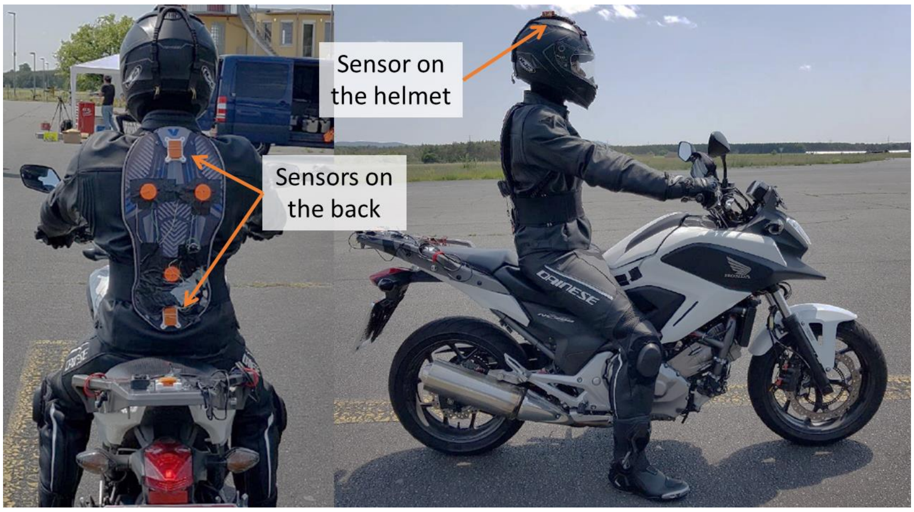


Figure 2. Positions of the three motion tracking sensors.

2.2 Experiments

For the autonomous braking maneuvers, the rider is asked to accelerate the motorcycle to a velocity of 70 km/h. At a certain point, the brake actuator is triggered via remote control by the test supervisor. The deceleration profile used during the experiments is the so-called 'block profile', which means that the brake pressure is built up with a maximum gradient (limited by the actuator) and held at the desired level until the vehicle stands still.

The decelerations achieved during the experiments were between 4 and 5 m/s^2. The desired brake pressures were reached within about 200 ms after the first triggering signal from the remote control. An example is shown in figure 3.

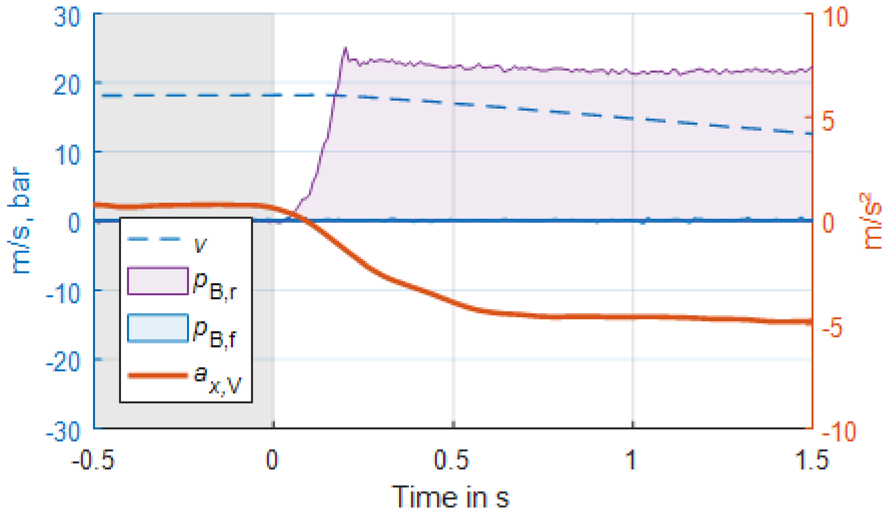


Figure 3. Acceleration curve for autonomous braking maneuver, triggering via remote control at $t = 0$.

For the comparison experiments, the rider is asked to decelerate the vehicle himself from the same initial velocity as before. In order to have a comparable vehicle behavior as in the autonomous braking maneuvers, in a first setup, the rider is asked only to use the foot brake lever. Thus the same brake force distribution (defined by the combined brake system) like in the triggered maneuvers can be expected. The rider is asked to perform a full braking and to actuate the brake as fast as possible. To also compare the autonomous deceleration to a realistic braking maneuver, in a second self-braking setup, the rider is asked to decelerate the vehicle with both brakes.

For all three experiments (autonomous braking, rider foot braking, rider hand braking), the following measurements are evaluated:

- Vehicle deceleration $a_{x,\mathrm{V}}$
- Brake pressures (front $p_{\mathrm{B,f}}$ and rear $p_{\mathrm{B,r}}$, at the brake cylinders)
- Rider upper body acceleration (shoulder blade level $a_{x,\mathrm{Rs}}$ and lumbar spine level $a_{x,\mathrm{Rl}}$)
- Head acceleration $a_{\mathrm{x,Rh}}$
- Force on handlebar F_{H} (measured orthogonally to the steering axis)
- Rotations about y-axis (upper body at shoulder blade level $\vartheta_{x,\mathrm{Rs}}$, upper body at lumbar spine level $\vartheta_{\mathrm{x,Rl}}$ and head $\vartheta_{\mathrm{x,Rh}}$,)

3 RESULTS

Figure 4 shows exemplary curves for the three different braking setups. The diagram shows the accelerations of the vehicle and of the rider's head and upper body. Additionally, the force the rider applies to the handlebar is shown. The exemplary curves for the different setups show characteristic effects that occur for all maneuvers of the same setup.

In general, the adaption of the rider accelerations ($a_{\mathrm{x,Rh}}$, $a_{x,\mathrm{Rs}}$, and $a_{x,\mathrm{Rl}}$) to the vehicle acceleration $a_{x,\mathrm{V}}$ takes more time in the autonomous braking maneuvers. Considering the fact that in the hand or foot braking maneuvers, the rider knows when he will apply the brake and can prepare for the maneuver by building up body tension in advance, this meets the expectations.

In the foot braking maneuver, a characteristic 'step' during the buildup of the body acceleration occurs for all maneuvers. In his normal sitting posture on the test motorcycle, the rider is not capable to fully apply the foot brake lever. Thus, reaching a specific point, he needs to adjust his position by shifting the whole body in positive x-direction before being able to fully apply the lever. This leads to a short interruption of the acceleration buildup.

In the hand braking maneuvers, the force on the handlebar F_H shows a specific behavior: After a short overshooting, it decreases and then increases again with a low gradient. Finally, the handlebar force reaches a higher level in the hand braking maneuvers compared to the autonomous and foot braking maneuvers.

Especially for the head acceleration, an overshooting effect before reaching the final level can be observed. This occurs for all three setups. While the overshooting ends faster for the hand braking than for the autonomous actuations, the foot braking shows a swinging behavior. This is probably again caused by the necessary body adjustment to an 'unusual' sitting posture while applying the foot brake lever.

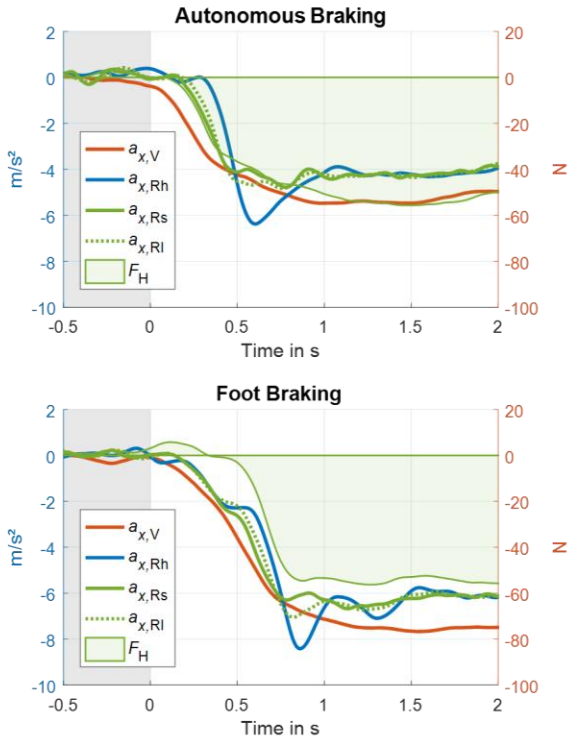


Figure 4. Characteristic curves for the different braking maneuvers.

The evaluation of the different measurements is described in the following subchapters.

3.1 Translational relative movement between rider and motorcycle

While the vehicle decelerates, the inertia of the rider body leads to a relative movement between the rider and his motorcycle in *x*-direction. The quality of the connection of the rider to his vehicle can be measured by the time he needs to adapt to the changing vehicle state. This is conducted by evaluating the time gap between the acceleration curve of the vehicle and the body accelerations (head, shoulder, lumbar spine). The time gap is determined for the point at which 50 % of the final deceleration level is reached. The 50 % level is chosen as in this phase the acceleration increases with a constant gradient for all maneuvers. The constant acceleration gradient phase is expected to be the main phase of the rider's adaption to the vehicle. Using the beginning or the end of the adaption phase would bear the risk to receive inaccurate results due to overshooting or oscillation effects. The final deceleration level is evaluated between $t = 1$ s and $t = 2$ s as a reasonably constant deceleration is reached then for all maneuvers.

This evaluation is performed for all three body accelerations. The authors assume a higher quality in the rider-vehicle-connection in the self-braking maneuvers than when the vehicle decelerates autonomously. An example for the determination of the head acceleration time gap $\tau_{50,Rh}$ in an autonomous braking maneuver is shown in figure 5.

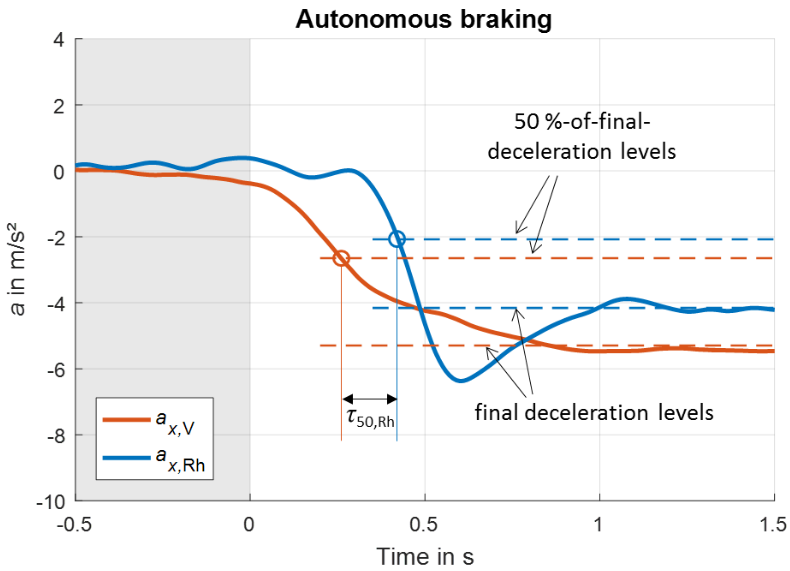


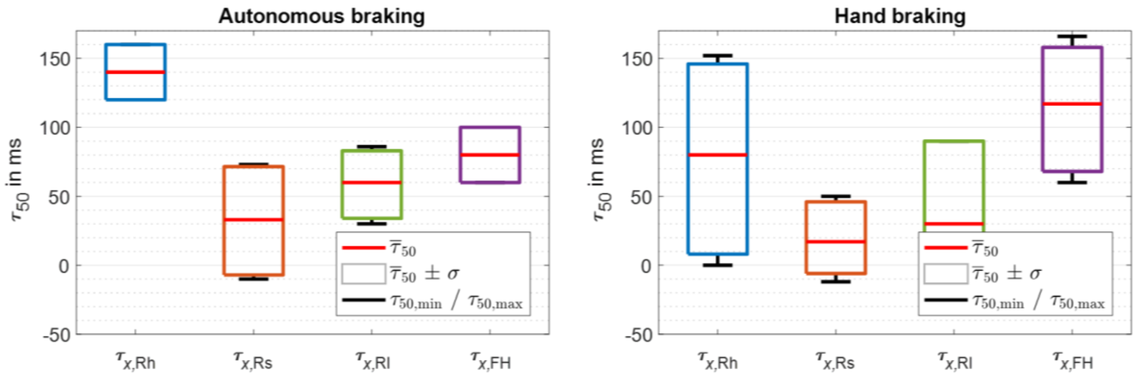
Figure 5. Determination of the $\tau_{50,Rh}$-time gap.

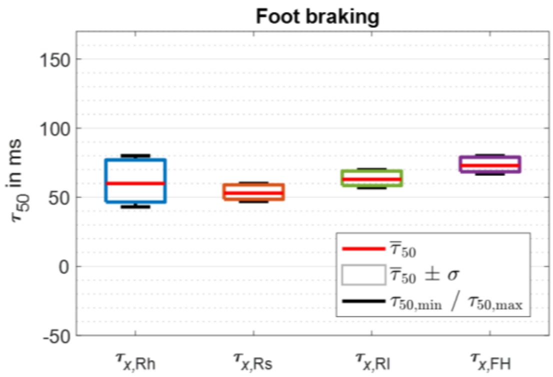
As the rider not only uses body tension to encounter the movement, but also supports his upper body by pushing himself back against the handlebar, this build-up of force on the handlebar is analyzed in the same way ($\tau_{50,FH}$). The mean τ_{50}-time gaps for accelerations and the handlebar force in the three braking setups are summarized in figure 6.

The results show that the most significant difference in the mean τ_{50}-time gap between the autonomous deceleration and the self-braking-maneuvers can be determined for the head acceleration ($\tau_{50,Rh}$). Two reasons can be assumed for this observation: Firstly, there is a long lever between the connection point to the vehicle (saddle) and secondly, the cervical spine is more mobile than the rest of the spine. This leads to the fact that it takes more time until the vehicle deceleration is transferred to the head. When the rider prepares for the maneuver before decelerating the vehicle himself by tensing his muscles, the deceleration transfer becomes more direct. As there is still a scattering, especially in the $\tau_{50,Rh}$ for the hand braking maneuvers, more experiments have to be performed to confirm the results.

The upper body acceleration time gaps ($\tau_{50,Rs}$ and $\tau_{50,Rl}$) are the shortest for the hand braking maneuvers. This is probably caused by the fact that the rider cannot support the movement against the handlebar as well as in the other maneuvers, as he needs to use the hand lever for braking. To be able to perform this task with the hand, the possible tension of the arm muscles is limited. Thus, the rider needs to support the movement more with upper body tension. The stiffer upper body leads to the smaller time gaps.

For the same reason, the time gap for the force on the handlebar is bigger for the hand braking maneuvers. The rider needs to have his hands ‘free’ to apply the brake and thus cannot tense the arm muscles to the same strength as in the other maneuvers. The lacking supporting force is compensated by upper body tension. Only when the brake and clutch levers are already applied, the rider can start to support his movement against the handlebar.





Mean time gaps ($\tau_{\overline{50}}$) for the different braking setups in ms

	$\tau_{\overline{50},Rh}$	$\tau_{\overline{50},Rs}$	$\tau_{\overline{50},Rl}$	$\tau_{\overline{50},FH}$
Autonomous braking	140	33.3	60	80
Hand braking	80	16.7	30	117.7
Foot braking	60	53.3	63.3	73.3

Figure 6. Mean $\tau_{50,Rh}$-time gaps for the different braking setups.

The evaluation of the translational relative movement shows, that the better connection between the rider and the motorcycle in the self-braking maneuvers can be shown best by the shorter time gaps of the head acceleration. The head is to a certain extent independent from the braking maneuver, while the upper body is influenced by the rider's motion while applying the hand or foot brake lever.

3.2 Rotation of the upper body within the sagittal plane

Another measurement to be considered when analyzing the rider state is the pitch movement of the rider during the braking maneuver. For this reason, the angular change of the upper body and head within the sagittal plane after the beginning of the braking maneuver is evaluated. Figure 7 shows the angular change $\Delta\vartheta$ for the three braking setups at the different measuring locations.

The angular changes of the upper body at the lumbar spine level and the shoulder level (upper diagrams in figure 7) follow very similar shapes. After a certain adjustment phase, the angles stay at a quite constant level. On average, the angular change is slightly higher for the autonomous braking maneuvers. This can (like the longer time gaps before) explained by the fact that the rider is surprised by the maneuver and thus cannot prepare for it in advance.

The curves of the head rotation (lower left diagram in figure 7) differ from those of the upper body. After a longer adjustment phase, the angle does not stay as constant as it does at the other positions. This can be explained by the high flexibility of the cervical spine. The most significant difference to the other positions is the relation between the angular change in the autonomous maneuvers and in the self-braking maneuvers. The change of the head angle is clearly higher for the autonomous maneuver due to the lacking opportunity to prepare for the deceleration. This becomes even clearer, when plotting the angular changes of the upper body against those of the head after the adjustment phase (shown in the lower right diagram in figure 7). In this diagram, two clusters can be distinguished: one for the autonomous braking maneuvers (upper right corner, blue markers) and one for the self-braking maneuvers (lower left corner, green and orange markers).

Like in the evaluation of the time gaps before, the head movement seems to be the most promising measurement to rate the quality of the connection between the rider and his vehicle.

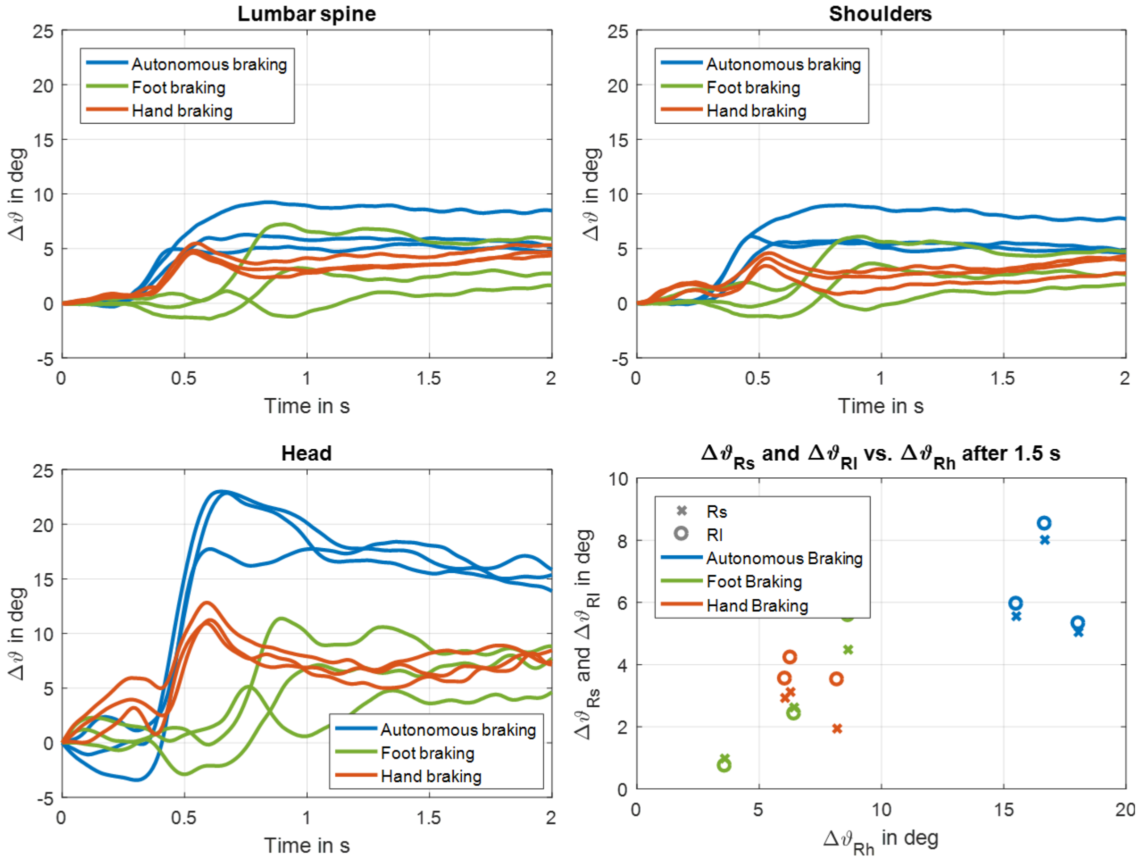


Figure 7. Angular change of rider upper body and head within the sagittal plane.

4 CONCLUSIONS

The evaluation of the different measures shows that the measures related to the head movement (translational relative movement and angular change in the sagittal plane) offer the most significant opportunity to show the quality of the connection between the rider and the motorcycle. By knowing the ‘usual’ behavior of a specific rider, e.g. by evaluating it with learning algorithms, in case of an autonomous emergency maneuver, the quality of the rider adaption could be evaluated in order to dynamically tune the autonomous maneuver. For riders who are capable to adapt to the changing vehicle state faster, the deceleration could be increased earlier to achieve a maximum reduction of kinetic energy prior to a crash.

The experiments described in this paper were all performed with the same rider. Assuming that different riders react to autonomous braking maneuvers differently in terms of needed time to adapt to the changing vehicle state, in future research, the experiments should be repeated with different rider types. By showing that the measures are suitable to identify different rider types, it could be possible to individually adapt autonomous decelerations to different riders in the future in order to optimize the maneuver, like explained before.

Due to the small number of repetitions of the different braking setups, the experiments only show tendencies, for a statistical evaluation and more robust results, more experiments with the same rider need to be performed in the future.

In the case of the described experiments, the rider knew that the motorcycle would autonomously decelerated. Only the moment when the deceleration happens was surprising. This could lead to the fact that with unprepared riders, the observed effects (e.g., longer time gaps for autonomous maneuvers could become even clearer.

REFERENCES

[1] I. Symeonidis, G. Kavadarli, E. Schuller, M. Graw, S. Peldschus, “Analysis of the stability of PTW riders in autonomous braking scenarios”, in: *Accident Analysis and prevention (49)*, 2012, pp. 212–222

[2] N. Merkel, R. Pleß, T. Hammer, N. Schneider, S. Will, „BASt FE 82.0661/2015 - Automatische Notbremssysteme für Motorräder”, *project report, to be published in 2019*

[3] N. Merkel, R. Pleß, H. Winner, “Tolerability of Unexpected Autonomous Emergency Braking Maneuvers on Motorcycles – a Participant Study”, *Proceedings of the Conference on The Enhanced Safety of Vehicles (ESV)*, Eindhoven, Netherlands, 9-13 June 2019,