Testing the acceptability of motorcycle-AEB system: use of unanticipated interventions as a reliable surrogate of genuinely unexpected events

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Abstract

Objective: Active safety systems such as motorcycle autonomous emergency braking (MAEB) capable of ensuring effectiveness and safe rider-vehicle interaction presents many potential benefits to reduce road fatalities but also many challenges. The whole development cycle of MAEB requires research through extensive field tests that reproduce unexpected interventions or real-life driving situation before the system can be available to the end-user. This study aims to better understand the rider's kinematic response required to control the stability of the rider-motorcycle system, as well as the extent of unexpectedness perceived by participants under different degrees of awareness of automatic braking (AB) activation.

Methods: We compared responses to AB in anticipated and (un)anticipated conditions and in a condition that was intended to be genuinely unexpected (*Out of the Blue*). Twenty men and women, wearing an inertial measurement unit on their upper-back, rode a scooter-type motorcycle with two front wheels simulating urban riding manoeuvres on a closed test-track. Three automatic braking (AB) profiles were tested in different sessions, ranged from 3 to 5 m/s^2 deceleration and 15 to 25 m/s^3 braking-jerk. Differences between AB conditions were analysed using linear mixed models.

Results: The unanticipated condition was perceived as fairly unexpected (rated between *Quite Unexpected* and *Very Unexpected*). *Out of the Blue* condition was on average close to the highest level of unexpectedness (*Completely Unexpected*). The exposure to unanticipated AB events resulted in upper-body response with larger peaks of pitch rate (0.20 to 0.77 rad/s higher) and acceleration (1.0 to 2.3 m/s^2 higher) than those of anticipated. Participants showed less postural stability during unanticipated events taking longer both to start correcting the initial forward lean and to fully stabilise balance. Unanticipated and *Out of the Blue* conditions did not differ in either the amplitude of the kinematic variables or the time-to-peak pitch rate.

Conclusions: The kinematic response of the rider's upper-body was found to be a reliable estimator of unexpectedness in AB. The findings suggest that unanticipated AB events while the rider engages in riding tasks can enable testing aimed at designing MAEB systems and assessing end-user acceptance in a reliable manner and within ethical safety limits.

Key Words: autonomous emergency braking, unexpected conditions, user acceptance testing, kinematic response, motorcycle crash, two-front-wheels.

INTRODUCTION

Crashes with motorized two- and three-wheeled vehicles cause the 28% of road fatalities around the world (WHO 2018). Riders of motorcycles and mopeds, vehicles named Powered Two-Wheelers (PTW), are exposed to higher crash and fatality risk compared to four-wheeled vehicle drivers. Previous research showed both that no evasive action by PTW riders accounted for 35% of multi-vehicle crashes involving PTWs and that when riders attempted to avoid the collision by braking, they braked poorly in 43% of cases (Huertas-Leyva et al. 2021). Autonomous Emergency Braking (AEB), an active safety system deployed in emergency situations taking control of the PTW, has been identified as one of the potentially most effective solutions to reduce PTW rider injuries (Savino, Mackenzie, et al. 2016).

AEB has been successfully implemented on four-wheeled vehicles and widely accepted by their drivers, who perceive it as fully reliable (Cicchino 2017). User acceptance of assistance systems such as AEB are essential, and will be achieved to the extent that the user believes that the fundamental objectives of system design (i.e., safety) and utility are met (Payre and Diels 2020). Implementing motorcycle autonomous emergency braking (MAEB) presents many potential benefits, but also many challenges. Investigating feasibility and effectiveness of MAEB, and specially its safe interaction with motorcyclists to design a system adapted to the rider, requires extensive research through field testing. Early research investigated the applicability of MAEB at 3m/s^2 through a mock-up sled (Symeonidis et al. 2012) and a motorcycle with pre-warned participants (Savino et al. 2012). Self-reports and qualitative observations of a series of randomly repeated automatic braking (AB) on a straight-path section alongside an unplanned AB also revealed that riders could consistently manage a gentle AB of 1.5m/s^2 (Savino, Pierini, et al. 2016). AB of 5m/s^2 were also studied with a dummy target vehicle running in front of the motorcycle (Merkel et al. 2019).

The design and development of a MAEB system with maximum safety impact requires new test procedures to determine the maximum deceleration capable of ensuring rider controllability and technical reliability. To achieve this, the MAEB system must undergo exhaustive testing reproducing unexpected automatic braking interventions or real-life scenarios to assess human responses and acceptance under different conditions. Since it is not possible to expose human volunteers to life-threatening scenarios, there is a general demand to find out how tests can be reliably performed in a controlled test-track minimising risk conditions (Beeman et al. 2012), so riders' tolerance and safety system reliability can be ethically studied without presenting additional risk of injury. Field testing in a controlled scenario may reduce the realism of emergency events, so the test design should avoid planning and preparation of movements in riders' response due to some degree of knowledge of an impending upcoming event (i.e., AB activation).

Previous research revealed that the unexpected condition, compared to the anticipated one, does affect manual braking in both response time (Davoodi et al. 2012) and initial braking jerk (Huertas-Leyva et al. 2019). However, those two variables, linked to manual braking response, are not applicable to quantify the effect of an unexpected AEB intervention on the rider. One of the most relevant sources of information about riders' response during unexpected events in which the vehicle takes control (e.g., AEB events) is body motion, being directly related to motorcycle rider stability. The effect of anticipatory information on the kinematic response to AEB activations has been reported previously for car occupants (Ejima et al. 2008; Östh et al. 2013). Unlike cars, for motorcycles, unwanted body movements, where the rider's postural stability may be compromised, can cause a significant change in the trajectory or in the worst case a loss of control of the vehicle and a crash (Huertas-Leyva et al. 2020). While the positive effects of MAEB on crash reduction and injury mitigation are beginning to be understood through early research on test-tracks, the effects of an unanticipated disturbance on the rider's response have not been well characterised. Maximum values of acceleration and rotational velocity of the rider's trunk during different types of falls in racing competitions have been reported in the past (Cossalter et al. 2007), but no kinematic threshold was set to identify when there was a high risk of losing control of the motorcycle. To the authors' knowledge, no studies have analysed the possible influence of unexpected automatic braking on the rider's posture to understand the consequence of such a response on rider-motorcycle stability.

Understanding the effect of active system interventions on rider movement is critical to ensuring the success of new motorcycle safety systems. This study aims to better understand the rider's kinematic response required to control the stability of the rider-motorcycle system, as well as to gain insights into the extent of unexpectedness perceived by participants under different degrees of awareness of AB activation. Following previous awareness classifications for brake reaction time studies (Young and Stanton 2007), we compared the rider's response to AB interventions in three awareness conditions (anticipated, unanticipated and unexpected). We wanted to assess whether unanticipated events, with rider performing different manoeuvres in a field test, trigger upper-body movements related to a completely unexpected intervention or whether, on the contrary, such events lead riders to anticipatory postural adjustments based on previous cues which guide how to respond and when to initiate the appropriate response.

METHODOLOGY

Participants and Vehicle

Twenty motorcycle riders participated in the experiment (demographics in Table A1 in the Appendix available in the online version as supplementary material). Participants had to own a full motorcycle licence for more than 2 years (or with at least 10,000km ridden) and to ride a PTW scooter (more than 74cc) at least once a week. Volunteers were invited through advertisements distributed via the University of Florence website, social networks, flyers and biker groups. The final selection of participants aimed to obtain a representative sample in age and gender of regular users of PTW scooters in Europe (Antov et al. 2012). This study was approved by the University of Florence ethics committee (Decision N. 46, 20/03/2019). The vehicle was an instrumented Piaggio MP3 500cc scooter with two-front wheels and ABS brakes. Acceleration, gyro, and orientation of the rider's upper-body were measured with an inertial measurement unit (IMU Xsens MTi-G) attached on the back of the safety vest, in the area between the 8th and 11th thoracic vertebrae (Figure 1). The vest was fitted to the torso of the participants, and it was verified that there was no looseness that could cause IMU displacement artifacts. Signals were sampled at 100 Hz. Considering that this was a pioneering study in AB activations in lateral manoeuvres without outriggers, to balance the risks involved we used a motorcycle with two tilting front wheels, thus offering higher stability and safety, while fully maintaining the typical single-track vehicle dynamics (Sponziello et al. 2008) including the possibility of capsizing.

The AB profile was characterised as an initial linear ramp-up (from 15 to 25 m/s^3 jerk) followed by the steady-state target deceleration (from 3 to 6 m/s^2). The AB event, which was triggered via a radio remote control, lasted about 1.2 seconds, which was insufficient for a complete stop. Throttle input was inhibited during AB interventions. More details about instrumentation in Lucci et al. (2021). Additional references can be found in the Appendix.

Test Procedure

After completing informed consent, participants performed rotational and lateral flexion movements on the motorcycle at standstill to establish a baseline calibration (Figure A1 in the Appendix of the online version). Next, participants completed a 10-15 minute practice ride to get familiar with the test vehicle and the closed test-track and all the manoeuvres that are included in the test. Such practice period was established as sufficient for the participants (Lucci et al. 2021). The familiarization ended with three braking manoeuvres to stop from 40km/h, with decelerations of 30, 60 and 90% of the participant's maximum performance. The familiarization phase was followed by testing AB activations under different awareness conditions (*anticipated, unanticipated* and *unexpected*). Table 1 summarises the test phases with their corresponding AB activations. For the *anticipated* condition phase, participants were asked to ride at a constant speed of 40km/h along a straight path of 100 meters in a dedicated track section (Figure A2 in the Appendix) and get prepared to an *anticipated* AB activation at a predefined location signalized by two cones. Participants were aware of the place and timing of activations exclusively through the instructions given by the operator before each run, without any other warnings. A total of up to four *anticipated* activations were performed, with increasing decelerations ranging from 3m/s^2 up to 6m/s^2.

For the *unanticipated* condition phase, a test course was designed to simulate urban riding manoeuvres including curving, accelerating and lane change. Participants were instructed: i) to ride around a 300m long test-track as they normally would and with no extreme manoeuvres until a flag was shown on the last straight indicating the end of the session; ii) to maintain the speed below 45 km/h; iii) to get prepared to *unanticipated* AB activations. In any case, participants were reminded that they could terminate at any time if they perceived that the experiment posed any risk to themselves by testing an AB intensity that was too high. This *unanticipated* phase included four sessions for all subjects, with a different AB setting for each session (nominal values: 3L= 3m/s^2 and (L)ower jerk 15m/s^3; 5L= 5m/s^2 and (L)ower jerk 15m/s^3; 3H= 3m/s^2 and (H)ighest jerk of 18m/s^3; 5H= 5m/s^2 and (H)ighest jerk 25m/s^3). The highest jerk levels for 3m/s^2 and 5m/s^2 were set to the maximum nominal values deployable by the system for each respective deceleration. In each session the participants made 12/14 laps, with two AB interventions made on the straight path and two in the lane change sector. The *unanticipated* condition implied that the participants did not know: the number of laps per session; the sequence or quantity of ABs per session; or *when* and *where* the AB would occur. This study explores previously untested automatic braking conditions that entail a risk of physical harm to volunteers. Given that volunteer safety is a primary concern as an ethical duty in human subjects research, the design of the experiment regarding participant exposure to the AB intervention had to find a compromise between optimal design and safety (Cozby and Bates 2018). Therefore, to minimise the risks of a fall during AB events, participant experienced unanticipated interventions having a progression in the required task; so, the first session deployed AB with 3L profile, considered safe for anticipated interventions in the literature (Savino, Pierini, et al. 2016) and the fourth session with the highest brake intensity (5H). Similarly, within the session, a pseudo-random order of activations was performed with three conditions: the first intervention was activated during the simplest manoeuvre (in a straight-line); the distance between two consecutive activations was at least one lap; and the fourth activation (the last one) was not before the eighth lap.

At the end of the last session, a genuinely unexpected activation was attempted by including an AB intervention in the straight sector of the second half of the test-track. This condition will be called *Out of the Blue* (*OB*). Figure A2 in Appendix shows the positioning of the AB interventions. The assumption was that having the whole return stretch of the track completely free from AB activations would induce participants to think that it was a *resting phase*, thus reducing the expectation for AB deployment. After each session, participants took a break of 5-10 minutes while they scored the expectedness of the AB interventions with a 7-point Likert rating scale. The overall duration of the test was no longer than two hours, the sessions were performed without incurring in any notable dangerous event.

The experimental design allowed direct comparison between: i) the *anticipated* and *unanticipated* conditions for the straight-line interventions with 3L, 5L and 5H automatic braking profiles; ii) the *unanticipated* and *Out of the Blue* condition for the 5L profile. ABs conducted with both the lane-change manoeuvre and the 3H profile, which were not tested in the *anticipated* condition, could not be compared. In such cases, only the straight-line events with 3H profile were analysed to measure the effect of session order when compared to those with 3L.

Characterization of the Rider's Kinematic Response

Longitudinal acceleration and pitch rate of the upper-body were registered and low-pass filtered (5 Hz cut-off). IMU axis were aligned to the body system using gravity and a standstill riding reference position for vertical orientation, and using principal component analysis methods with data collected on a straight riding section with AB event for horizontal orientation (Kunze et al. 2009). Using the rotation matrix with the angles registered in each instant, we computed the longitudinal acceleration of the body. The acceleration and angular velocity vectors are presented in a fixed vehicle coordinate system (Figure 2). A set of variables was defined to characterise the body response and quantify the magnitude of the balance perturbation caused by the AB intervention (Figure 3). The amplitude of the response was measured with the *peak* acc_{rel}, computed as the difference between steady-state vehicle deceleration of *a_MC* (i.e., 3 or 5m/s^2) and the peak longitudinal deceleration of the rider (*a_Body*), and with the *peak pitch-rate*, associated with the flexion–extension movement of the trunk. Time-to-peak (TTP) of both acceleration (*TTP-Acc*) and pitch rate (*TTP-Pitch-rate*) characterised the timing of the kinematic response. TTP is counted from the actual AB onset actuating on the wheels, i.e., after the system latency.

Statistical Analysis

To compare volunteers' ratings of perceived unexpectedness in each of the sessions, we performed Wilcoxon signed-rank test. To test the hypothesis that rider response to an *unanticipated* automatic braking differs from that of *anticipated* and *Out of the Blue* conditions, we used a linear mixed-effects model including AB-condition as fixed factor with random intercepts and as covariates the potential confounding factors *AB-decel*, *AB-jerk* and initial speed at AB triggering (*Velocity_ini*). Since the body response for big differences between AB settings was not linear, an analysis of the effect of awareness condition on body movement was performed for each AB setting. The best fit model was defined by the number of parameters and the -2 Log likelihood. Furthermore, to identify possible learning effects, the effect of the order of AB intervention within and between sessions was analysed. For the within-session effect (first vs. second AB in straight-line), a repeated measures ANOVA was performed for each session. For the between-session learning effect, we compared the rider response of the sessions with the most similar AB profile (3L in the first session and 3H in the third session) by conducting linear mixed models using session order as a fixed effect, pilot response characteristics as the dependent variable, and *AB-decel* and *AB-jerk* as covariates to control for differences between AB profiles. Significance was set at an alpha of 5%.

RESULTS

Perceived Unexpectedness

In all four sessions the average score for the *unanticipated* AB interventions was between '+1 = *Quite Unexpected'* and '+2 = *Very Unexpected'* (Figure 4). Overall, the trend of the average score of *Unexpectedness* along the four sessions decreased, but these differences were not significant (*p* range [0.130 -0.705]). AB interventions in the *Out of the Blue* condition were considered more unexpected than the *unanticipated* interventions tested in any of the four sessions (*p* range = [0.000 – 0.031]). *Out of the Blue* event was rated by 45% of the participants with the highest level of *Unexpectedness* ('+3 = *Completely Unexpected'*). Detailed results in Table A3 in Appendix.

AB Conditions: Deceleration, Jerk and Initial Speed

Typical AB activation profiles, including a system latency of 0.1s before activation of the brakes on the wheel are shown in Figure A3 in the Appendix. The average values of steady deceleration, braking-jerk and initial speed at AB triggering for each of the four AB-settings are presented in Table A2 in the Appendix. We found a trend to have slightly higher deceleration and jerk in *unanticipated* condition over the *anticipated* one in the three comparable AB settings. Such small differences, despite having the same settings in both conditions, could occur due to cold brakes during *anticipated* AB interventions. *Velocity_ini* was in the range of 40-50km/h as instructed. Data confirmed that the highest jerk deployable for 3m/s^2 and 5m/s^2 of steady deceleration differed due to system limitations (averages around 25m/s^3 for 5H and of 17.9m/s^3 for 3H). Comparing *unanticipated* and *OB* conditions, deceleration and jerk did not differ; *Velocity_ini* was 7.7km/h higher on average in *OB* condition. All these variables were controlled within each condition as potential confounders in the linear mixed model.

Upper-Body Kinematic Response

Unanticipated vs. Anticipated

Beyond possible confounders, an increase in both the *peak accelerations* and in the *peak pitch-rate* of the upper-body (Figure A4 and A5 respectively from supplementary data in online version) was evident during the *unanticipated* AB events. Observational data noted that in the *unanticipated* interventions, in general, acceleration and pitch rate of the upper-body showed considerable variability across individuals in the amplitude of the oscillations. In contrast, the response across riders seems more uniform for *anticipated* AB events (the lower the AB intensity the more uniform). The linear mixed models evaluating the effect of AB awareness condition included as covariates the potential confounders *AB-decel* and *AB-jerk*. *Velocity_ini* was found not significant. Summary statistics for each dependent measure are shown in Table 2. The results found significant effect of the AB awareness condition on *peak* acc_{rel} and *peak pitch-rate* of the upper-body in all the three AB settings compared. The *unanticipated* condition in AB events for a rider performing a series of urban manoeuvres on-track, compared to that *anticipated*, increases on average between 1.0 and 2.3 m/s^2 the peak backward acceleration and between 0.2 and 0.8 rad/s the *peak pitch-rate*. We also found a significant increase in *TTP-Acc* when the participant was not warned for each of the three AB profiles analysed (increase between 0.08s and 0.11s on average). *TTP-Acc* may be related to time to take the control, so longer *TTP-Acc* may be related to longer reaction time to stabilize the response during automatic braking. *TTP-Pitch-rate* differed between awareness conditions only for the highest AB setting, and it represented as little as 0.02s difference.

In most cases, *peak acceleration* came later than *peak pitch-rate* to compensate the forward pitching of upper-body. Two observations are worth noting: i) braking profile with the longer time of ramp-up (5L) presented the longest TTPs and, similarly, the one with the shortest time of ramp-up (5H) had the shortest TTPs; ii) for all three AB profiles, the peaks of *pitch-rate_body* and *a_body* came after the end of the ramp-up.

Unanticipated vs *Out of the Blue*

The linear mixed model performed included *AB-decel* and *AB-jerk* as covariates. *Velocity_ini*, not significant, was not included in the final analysis. There were no significant differences between *unanticipated* and *Out of the Blue* condition in the amplitude of the kinematic response – F (1, 38.9) =1.40, $p = 0.244$ for *peak* acc_{rel} and F (1, 38.6) = 0.184, $p = 0.670$ for *peak pitch-rate*. No differences in *TTP-Pitch-rate* were found neither – F (1, 38.9) =0.228, $p = 0.636$. Only the TTP of body acceleration was found different – F (1, 38.8) =12.75, $p < 0.001$ –, but with estimated means differing as little as 0.04s. the summary statistics for each dependent measure is shown in Table A4 in the Appendix. Figure 5 shows how the trials in *anticipated* condition are distributed around the area of lower peaks of the kinematic variables and that, in contrast, those in *unanticipated* and *Out of the Blue* conditions have both higher variability and larger peaks.

Sequence of upper-body kinematic response to AB interventions

Rider response analysis identified three stages in the kinematic response after the AB system initiated to brake the motorcycle (Figure 6). In S1 (0.0 to 0.2s) there is a period where the absolute value of *a_body* is lower than that of the *a_MC*, which indicates upper-body is accelerating forward because of the inertial force generated by the AB. In general, this period is longer in the *unanticipated* condition and is also related to the intensity of the braking-jerk. The upper-body also starts to rotate forward at S1. In S2 (0.2 to 0.6s) the rider compensates the inertial force and stabilizes the postural balance with the reaction force from handlebar and footplate. The peak of *a_body* is reached in S2, usually before 450ms. In most cases, the *peak acceleration* came later than the *peak pitch-rate* to compensate for the forward pitching of the upper-body. The initial forward torso rotation typically ends at around 0.5s at this stage. After 0.6s (S3), the upper-body acceleration and pitch rate are fully stabilized without significant oscillations in the case for *anticipated* interventions, whereas for *unanticipated* ones the stabilization phase takes longer (with high inter-rider variability).

Learning Effect

No significant effect of within-session activation order on body kinematic response was found (*peak* acc_{rel}, *peak pitch-rate, TTP-Acc, TTP-Pitch-rate*) when comparing the first and second *unanticipated* AB event in straight-line in sessions with 3L, 5L or 5H settings (Table 3). After comparing the first and third session in AB for $3m/s^2$ deceleration in straight-line, we also found no significant effect of session order on *peak* acc_{rel}, *peak pitch-rate, TTP-Acc,* and *TTP-Pitch-rate* with *AB-decel* and *AB-jerk* controlled as covariates in the linear mixed model (detailed results in Table A5 in the Appendix).

DISCUSSION

This study aimed to understand how different levels of awareness of the occurrence of automatic braking (AB) events affect both motorcyclists' response to control postural stability and perceived unexpectedness. Specifically, we wanted to know whether the upper-body kinematic response to unanticipated interventions was comparable to that of an unexpected condition or, given the context of an experimental test, was similar to that in which the AB is fully expected (anticipated). *Unanticipated* activations were perceived by participants as between *Quite unexpected* and *Very unexpected* in all four test sessions. The unexpectedness level of the *unanticipated* condition was lower than that of the *Out of the blue* (*OB)* event, which was rated on average close to the maximum unexpectedness level (*Completely Unexpected*). As intended in the experimental design, the test captured elements of the surprised behaviour during the *OB* event, which resulted a genuinely unexpected event (or nearly so) for almost all the participants.

This work revealed that *unanticipated* condition led to a kinematic response with higher amplitudes than those measured in *anticipated* condition. Participants also showed less postural stability during *unanticipated* events compared to those *anticipated*, as they took longer to start correcting the initial forward trunk lean and to fully stabilise balance without significant oscillations. Results suggest an anticipatory response during fully expected AB events, where riders balanced the AB inertial force with an earlier and more controlled response; probably facilitated by an increase in arms stiffness that provided resistance to the initial forward motion, converging to a stable position quicker. In contrast, the rider's balance control response during the *unanticipated* AB events was reactive (Figure A6 in the Appendix). Comparing upper-body response of *unanticipated* and *OB* condition, no significant differences were found in either the amplitude of the kinematic variables or the time-to-peak of pitch rate. This result suggests that the compensatory postural adjustments during *unanticipated* AB events with participants engaged in riding manoeuvres can be comparable to that of an unexpected event. Our finding differs from Symeonidis et al. (2012) who, after testing eight participants with backward accelerations (3.0-3.5m/s^2) on a mock-up-sled, reported that *pre-warning* versus unanticipated condition did not affect head and torso kinematics. Some differences with that earlier study may justify these discrepancies: i) *pre-warning* condition entailed haptically informing the volunteers 300 ms before the deceleration started; ii) the balance control with the implicit instability of real motorcycle requires a more complex response; iii) participants in our results were distracted in a riding task that could reduce situation awareness making the *unanticipated* AB intervention more unexpected. Assuming that during the anticipated conditions the riders were in a tense state, our findings are consistent with previous studies for cars based on sled tests (Ejima et al. 2008) which found that when volunteers were instructed to be in tension, the resulting stiffness of the extremity joints decreased upper-body motion compared to the body's response when relaxed.

The effect of exposure to repeated *unanticipated* AB events in individual sessions and between the first and the third session was investigated. We did not observe any gradual, anticipatory shift in kinematic response. This finding together with that of the subjective response discussed previously suggests that, for a limited number of repetitions in unanticipated condition with the participant engaged in riding manoeuvres, the effect of repeated exposure to automatic braking on both anticipatory control and expectancy level was non-significant. Preceding studies with AEB and car occupants presented conflicting results, finding that the maximum displacement rate of head and trunk for the first repetition did not differ from the second (Graci et al. 2019) and, in contrast, that the EMG onset time of the upper-body muscles was faster in the fourth exposure to autonomous braking than in the first (Östh et al. 2013). Yet, we should note the limitations of direct comparison with studies with car occupants, as the control of body balance in motorcycle riding is much more complex and involves stabilizing the rider-vehicle system. This may make adapting strategies to restore postural balance more complex during unexpected ABs, resulting in a longer adaptation process for motorcyclist than for car drivers.

The proposed protocol and the layout in the test-track enabled riding control tasks similar to that found in real-life conditions, surpassing the risk and realism of any lab testing, but still with the limitations associated with testing in controlled conditions in terms of activating the life-threatening nature of real emergency events. The fact that this is a pioneering field study on motorcycles with real AB systems and new braking intensities (deceleration of 5m/s^2 and jerk above 15m/s^3) including lateral manoeuvres without outriggers brought some limitations to the study that were necessary for safety (and ethical) reasons, described as follows.

Not counterbalancing awareness conditions order was assumed on one hand because it was expected that experiencing *unanticipated* condition first would weigh heavily on the participants' subsequent response in *anticipated* condition. Therefore, the proposed design could affect the magnitude of the difference between awareness conditions, but not the finding of identifying an anticipatory response in the first (*anticipated*) condition and reactive response in the second (*unanticipated*). Furthermore, to induce the unexpected event without deceiving subjects, and to ensure that they could comply with all programmed activations, the *OB* condition was necessarily always performed last. Therefore, inadvertent adaptation between sessions could have counteracted the effect of the *OB* interventions, leading to a smoother and more controlled response to stabilize the vehicle. However, the fact that the peak values of pitch rate and upper-body acceleration occurred in the last session just before the *OB* condition, together with the absence of learning effect found within and between sessions, suggest that the adaptation effect had little influence on the body's response compared to the effect of the awareness condition and the AB profile.

Having demonstrated the possibility of performing our test conditions on experienced riders under low risk, future research is warranted to further explore: i) the learning effect of repeated exposures on the control of the motorcycle by randomising the awareness conditions and AB intensities; ii) the broad generalisability of our results for motorcycles with different characteristics from those of a scooter model with two front wheels (still capsizing, but with higher stability). It is also recommended to study how collision warning in a MAEB may affect the motorcyclist situational awareness by analysing the kinematic response, to understand whether, in a real-life scenario with a collision warning, the rider's response to MAEB interventions is close to that of the unanticipated condition of our tests. Or rather, on the contrary, riders have enough time to react with a proactive control balance response as shown in the anticipated intervention.

The results reinforced the hypothesis that a test under conditions as those defined in our experiment, in which motorcyclists are exposed to unanticipated AB events while performing different manoeuvres, may be valid for a close-to-reality assessment of motorcyclists' responses to MAEB activations with a surprise component. The use of unanticipated events on test-track as surrogates for unexpected ones in the real-life conditions can enable the experimentation required in the design of active safety systems that momentarily take control of the motorcycles. With such testing, the acceptance of system settings and the risk of loss of control can be assessed reliably and within ethical safety limits. Notably, the data collected can be increased by measuring riders' response in more than one unanticipated event through repeated measures design, thus controlling for between-subject variability and reducing sample size. As a result, the development process of a promising system such as MAEB can be accelerated before executing the last phase, where the safety impact and acceptance of the on-road system is measured in real traffic.

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FIGURES

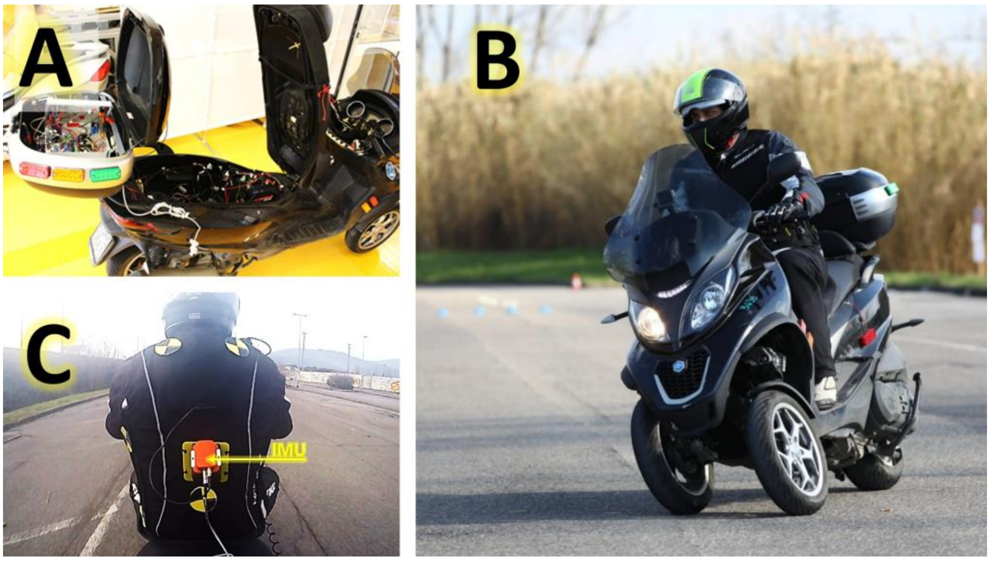

Figure 1. **Vehicle instrumented in the lab (A) and on the test-track (B). IMU position on participant (C).**

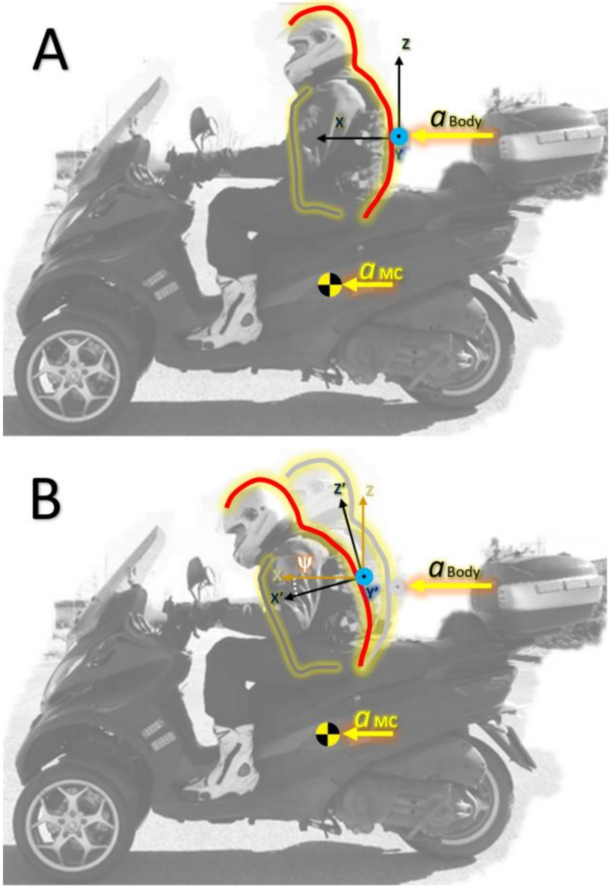

Figure 2– Example of vector of longitudinal acceleration of the motorcycle (*a_MC*), longitudinal acceleration of upper-body (*a_Body*), and differences in pitch (ψ) for upper-body. A) trunk at right angle; B) flexion movement of ψ radians. *Pitch-rate* > 0 refers to forward pitch rotation (flexion) and *a_Body* < 0 to backward acceleration

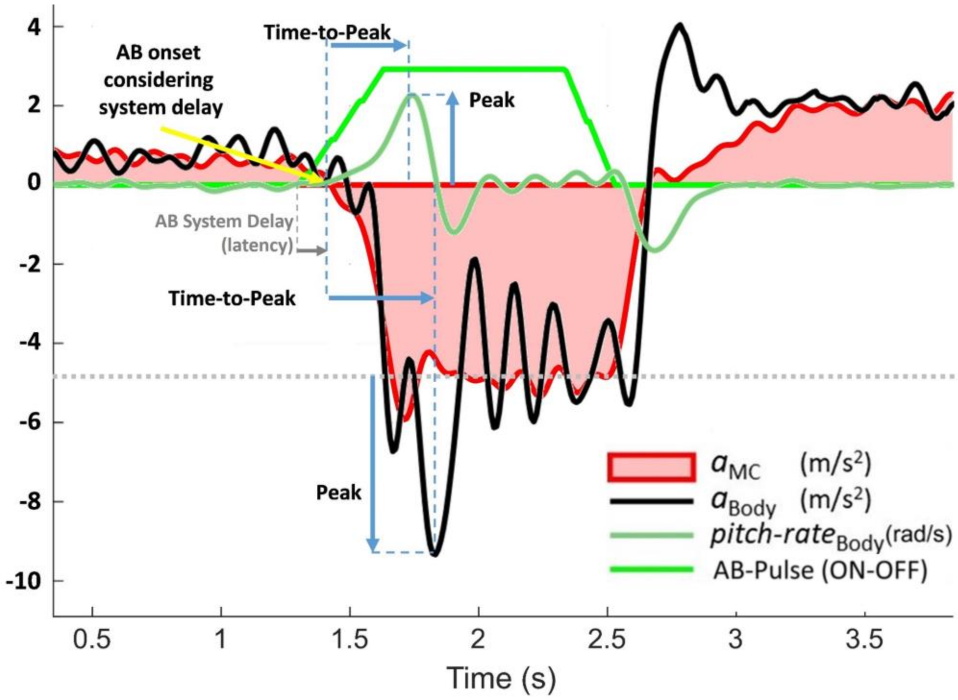

Figure 3 – Example of AB-event with the representation of the parameters characterizing the upper-body response. *AB-Ref* represents the reference signal followed by the AB activation.

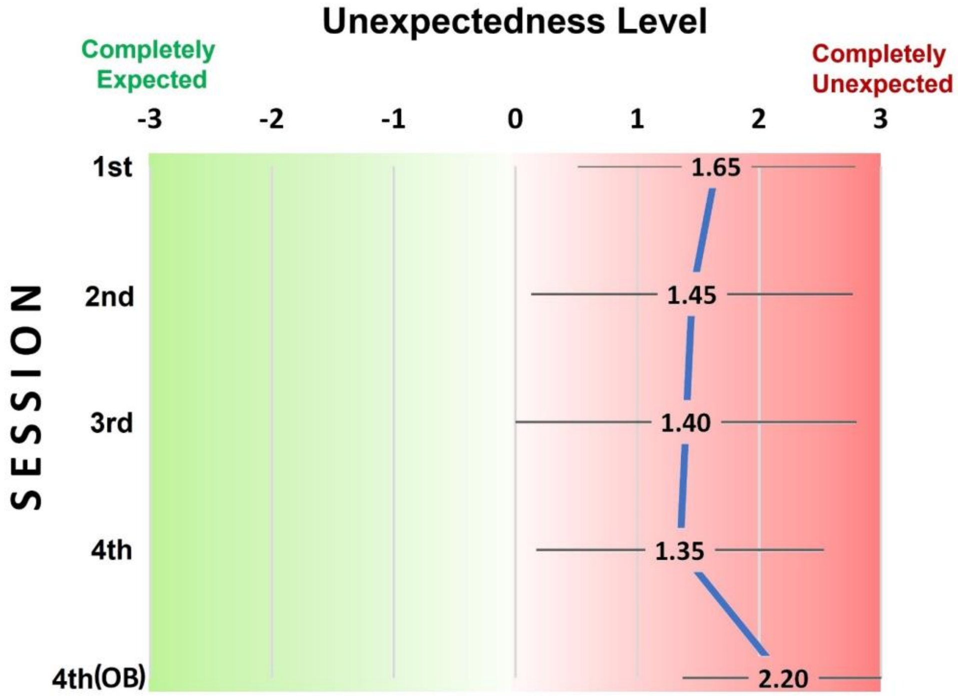

Figure 4. Mean ±1SD of the Subjective Rating of Unexpectedness for each Session (Unexpectedness level scale: [-3=*Completely Expected*, +3=*Completely Unexpected*]), N=20.

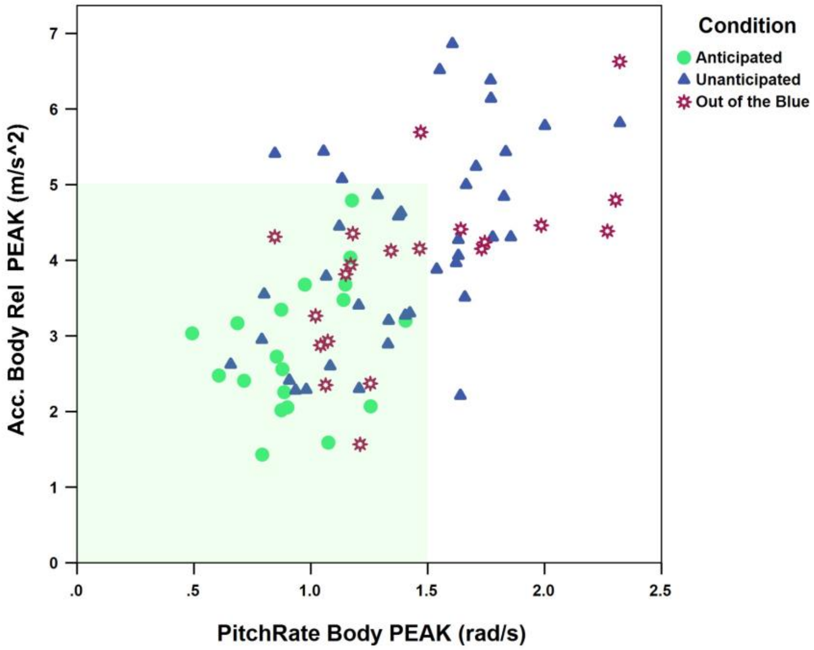

Figure 5. Scatter plot of the peaks of the kinematic parameters of the upper-body response for automatic braking of 5L profile for the three aware conditions tested. (Magnitudes from the tests, without controlling *AB-decel* and *AB-jerk*). The shaded area covers all responses with *anticipated* AB.

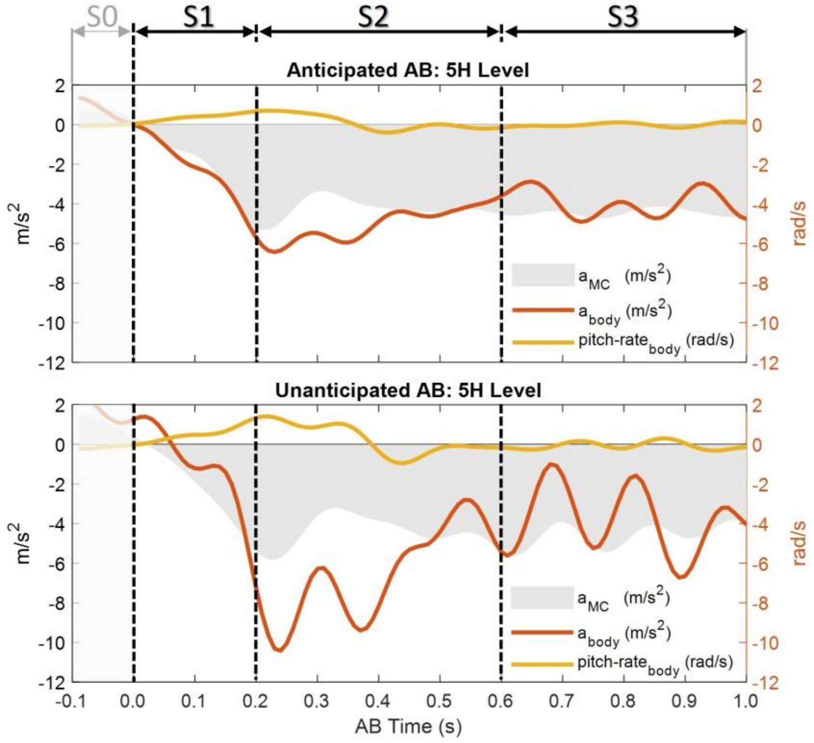

Figure 6. Response of a typical subjects for AB in *unanticipated* and *anticipated* condition (5H profile). Time series of event AB for motorcycle acceleration (a_{MC}), and upper-body acceleration and pitch rate. The vertical grey dashed lines separate the different stages identified. Normalized time -0.1s corresponds to the AB trigger and the vertical line at 0s represents the actual braking onset after the system response latency. Positive pitch rate represents a forward rotation.

TABLES

Table 1- Test Procedure: Summary of the AB activations of the test protocol

AB-Condition	Session	AB Level	Manoeuvre	AB activations per rider (N)	Laps (N)
Anticipated	0	3L	Straight-line	1	1
		5L		1	1
		5H		1	1
		*6L		1	1
Unanticipated	1	3L	Straight-line $^+$Lane change	2 2	12-14
					Questionnaire_1
	2	5L	Straight-line $^+$Lane change	2 2	12-14
					Questionnaire_2
	3	*3H	Straight-line $^+$Lane change	2 2	12-14
					Questionnaire_3
	4	5H	Straight-line $^+$Lane change	2 2	12-13
Out of the Blue	4	5L	Straight-line	1	1
					Questionnaire_4 + General Survey

**Anticipated* and *Unanticipated* condition cannot be compared
$^+$ out of the scope of this study
AB setting nominal values:
3L: 3m/s^2 deceleration and Lower jerk (15m/s^3); 5L: 5m/s^2 deceleration and Lower jerk (15m/s^3)
3H: 3m/s^2 deceleration and Highest jerk (18m/s^3); 5H: 5m/s^2 deceleration and Highest jerk (25m/s^3)
6L: 6m/s^2 deceleration and Lowest jerk (15m/s^3)

Table 2. Subset of parameters of kinematic response with estimated mean (standard error in brackets) for all participants divided into the experimental conditions *unanticipated* and *anticipated* and for three different AB settings. TTP values counted after the 100ms of delay of activation after triggering.

Variable	AB level	Condition		Mean Diff (std. error)	F(d.f.); *p*
		Anticipated	Unanticipated		
Peak Acc Rel (m/s^2)	3L*	2.15 (0.24)	3.16 (0.20)	+1.01 (0.25)	F (1, 43.6) =16.17; $p < 0.001$
	5L*	3.09 (0.30)	4.12 (0.22)	+1.04 (0.35)	F (1, 52.7) =8.77; $p = 0.005$
	5H*	3.24 (0.42)	5.54 (0.31)	+2.30 (0.48)	F (1, 47.2) =22.70; $p < 0.001$
Peak Pitch-Rate (rad/s)	3L*	0.68 (0.04)	0.88 (0.03)	+0.20 (0.04)	F (1, 44.8) =21.63; $p < 0.001$
	5L*	0.99 (0.08)	1.36 (0.06)	+0.37 (0.10)	F (1, 54.2) =13.99; $p < 0.001$
	5H*	1.20 (0.12)	1.97 (0.09)	+0.77 (0.12)	F (1, 47.4) =38.55; $p < 0.001$
TTP-Acc (s)	3L*	0.26 (0.02)	0.37 (0.01)	+0.11 (0.03)	F (1, 56) =19.54: $p < 0.001$
	5L*	0.31 (0.02)	0.41 (0.02)	+0.10 (0.02)	F (1, 51.7) =22.33; $p < 0.001$
	5H*	0.26 (0.02)	0.34 (0.01)	+0.08 (0.02)	F (1, 56.0) =17.47; $p < 0.001$
TTP Pitch-Rate (s)	3L	0.26 (0.01)	0.28 (0.01)	n.s.	F (1, 56.0) =1.88; $p = 0.176$
	5L	0.32 (0.01)	0.31 (0.01)	n.s.	F (1, 55.0) =0.94; $p = 0.338$
	5H*	0.25 (0.01)	0.27 (0.01)	+0.02 (0.01)	F (1, 46.76) =5.68; $p = 0.021$

*p <0.05 = significant; n.s. = not significant
Estimated means with covariates in the mixed model evaluated at the following values.
3L: Decel AB = 3.09 m/s^2, Jerk AB = 14.4 m/s^3.
5L: Decel AB = 4.57 m/s^2, Jerk AB = 18.2 m/s^3.
5H: Decel AB = 5.15 m/s^2, Jerk AB = 26.4 m/s^3.

Table 3. Results for the Repeated means ANOVA for the within-session effect of the order activation in straight-line (first versus second)

Parameters	**AB level**	**F(d.f.); *p***
Peak Acc Rel	3L	F (1, 19) = 0.038; *p*=0.848
	5L	F (1, 19) = 0.131; *p*=0.722
	5H	F (1, 19) = 1.534; *p*=0.231
Peak Pitch-Rate	3L	F (1, 19) = 1.533; *p*=0.231
	5L	F (1, 19) = 2.182; *p*=0.156
	5H	F (1, 19) = 0.090; *p*=0.767
TTP-Acc	3L	F (1, 19) = 0.426; *p*=0.522
	5L	F (1, 19) = 3.095; *p*=0.095
	5H	F (1, 19) = 0.529; *p*=0.476
TTP-Pitch-rate	3L	F (1, 19) = 0.435; *p*=0.517
	5L	F (1, 19) = 1.343; *p*=0.261
	5H	F (1, 19) = 4.208; *p*=0.054

TESTING THE ACCEPTABILITY OF MOTORCYCLE-AEB SYSTEM: USE OF UNANTICIPATED INTERVENTIONS AS A RELIABLE SURROGATE OF GENUINELY UNEXPECTED EVENTS.

Pedro Huertas-Leyva (corresponding autor: pedro.huertasleyva@unifi.it), Giovanni Savino, Niccolò Baldanzini

APPENDIX WITH SUPPLEMENTAL MATERIAL

TABLES

Table A4. Demographics of the Participants

Sample Size (Men, Women)	20 (16, 4)
Age (years): mean (sd), [min, max]	37.6 (11.2), [22, 57]
Height (cm): mean (sd), [min, max]	174.9 (6.2), [158, 185]
Weight (kg): mean (sd), [min, max]	74.3 (11.2), [54, 95]

Table A5. Average ± standard deviation of potential confounders for the comparative analysis of AB conditions.

AB Parameter	***AB- Level***	***Anticipated***	***Unanticipated***	***Out of the Blue***
Deceleration (m/s²)	3L	3.0 ± 0.3	3.1 ± 0.2	
	5L	4.3 ± 0.3	4.7 ± 0.4	4.8 (0.6)
	5H	5.0 ± 0.3	5.2 ± 0.5	
	3H		3.2± 0.3	
Braking Jerk (m/s³)	3L	12.9 ± 1.7	15.2 ± 3.4	
	5L	16.9 ± 1.8	18.9 ± 3.3	19.1 (3.5)
	5H	24.2 ± 3.5	27.6 ± 4.5	
	3H		17.9 ± 4.3	
Velocity Ini (km/h)	3L	41.1 ± 4.2	41.0 ± 3.7	
	5L	44.3 ± 3.6	41.1 ± 4.7	48.8 (5.6)
	5H	45.4 ± 4.8	41.9 ± 4.4	
	3H		41.3 ± 4.1	

Table A6. Wilcoxon Signed Ranks Tests for Perceived Unexpectedness

Sessions [AB-Level]	Z	*p*
OB vs. 1st[3L]*	-2.16	0.031
OB vs. 2nd[5L]*	-2.95	0.003
OB vs. 3rd[3H]*	-2.94	0.003
OB vs. 4th[5H]*	-3.56	0.000
1st[3L] vs. 2nd[5L]	-0.91	0.366
1st[3L] vs. 3rd[3H]	-*1.32*	0.187
1st[3L] vs. 4th[5H]	-*1.51*	0.130
2nd[5L] vs. 3rd[3H]	-*0.38*	0.705
2nd[5L] vs. 4th[5H]	-*0.63*	0.527
3rd[3H] vs. 4th[5H]	-*0.38*	0.705

*p <0.05 = significant difference.
3L = 3m/s^2 and Lower jerk; 5L = 5m/s^2 and Lower jerk;
3H = 3m/s^2 and Highest jerk; 5H = 5m/s^2 and Highest jerk;
OB= *Out of the Blue*

Table A7. Subset of parameters of kinematic response with estimated mean (standard error) for the linear-mixed-model comparing the experimental conditions *Unanticipated* and *Out of the Blue* for the AB level 5L. TTP values counted after the 100ms of delay of activation after triggering.

	AB	**Condition**		**Mean Diff**	**F(d.f.); *p***
Variable	**level**	**Out of the Blue**	**Unanticipated**	**(std. error)**	
Peak Acc Rel **(m/s^2)**	5L	3.90 (0.27)	4.23 (0.21)	n.s.	F (1, 38.9) =1.40 *p* = 0.244
Peak Pitch Rate **(rad/s)**	5L	1.45 (0.08)	1.41 (0.06)	n.s.	F (1, 38.6) =0.184 *p* = 0.670
TTP-Acc* **(s)**	5L	0.36 (0.02)	0.40 (0.01)	+0.04 (0.01)	F (1, 38.8) =12.75 *p* < 0.001
TTP Pitch Rate **(s)**	5L	0.31 (0.01)	0.31 (0.01)	n.s.	F (1, 38.9) =0.228 *p* = 0.636

*p <0.05 = significant; n.s. = not significant
Estimated means for 5L with covariates in the mixed model evaluated at the following values: AB-decel = 4.74 m/s^2, AB-jerk = 18.9m/s^3

Table A8. Between-session effect of the order activation. Subset of parameters of kinematic response with estimated mean (standard error in brackets) for the linear-mixed-model comparing 1st session versus 3rd, both with AB of 3m/s2. TTP values counted after the 100ms of delay of activation after triggering.

Parameter	***3L (1st)*** [a]	***3H (3rd)*** [b]	**Mean Diff (std. error)**	**F(d.f.);** ***p***
Peak Acc Rel (m/s^2)	3.44[c] (0.23)	3.69[b] (0.24)	n.s.	F(1, 59.4)=0.797 *p* = 0.376
Peak Pitch-Rate (rad/s)	0.947 [c] (0.042)	0.963 [c] (0.044)	n.s.	F (1, 53.8) =0.169 *p* = 0.683
TTP-Acc (s)	0.349 [c] (0.014)	0.328 [c] (0.015)	n.s.	F (1, 68) =1.001 *p* = 0.321
TTP-Pitch-Rate (s)	0.269 [c] (0.011)	0.250 [c] (0.012)	n.s.	F (1, 57.5) =2.314 *p* = 0.134

[a] average ± standard deviation of the AB parameters: Decel AB = 3.1 ± 0.2 m/s^2 and Jerk AB = 15.2 ± 3.4 m/s^3

[b] average ± standard deviation of the AB parameters: Decel AB = 3.2 ± 0.3 m/s^2 and Jerk AB = 17.9 ± 4.3 m/s^3

[c] Estimated means were computed with covariates evaluated at the values: Decel AB = 3.17 m/s^2, Jerk AB = 16.4m/s^3

FIGURES

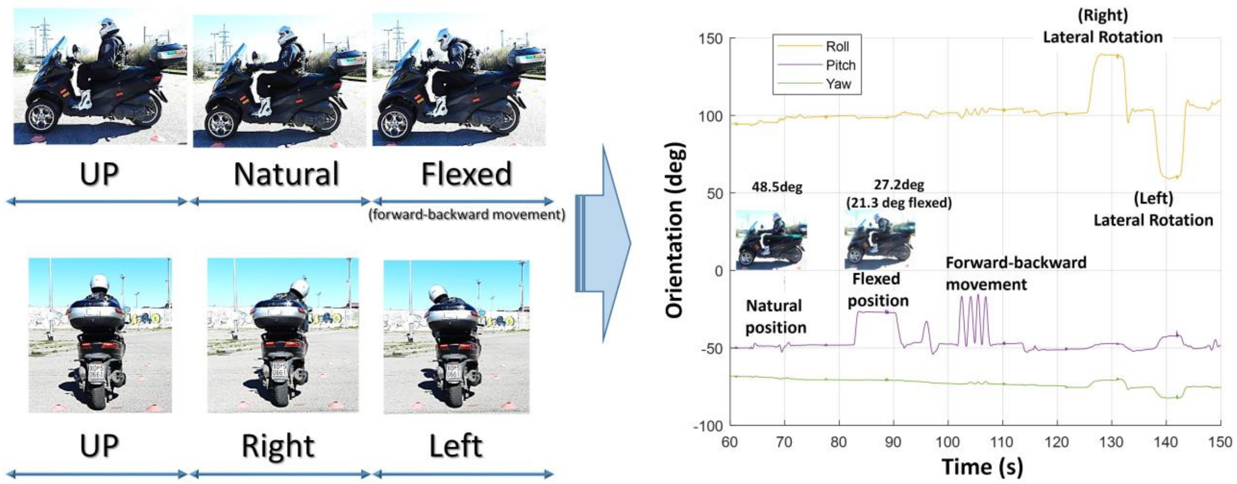

Figure A7. Procedure for calibration baseline of the IMU attached on upper-body of the motorcycle rider.

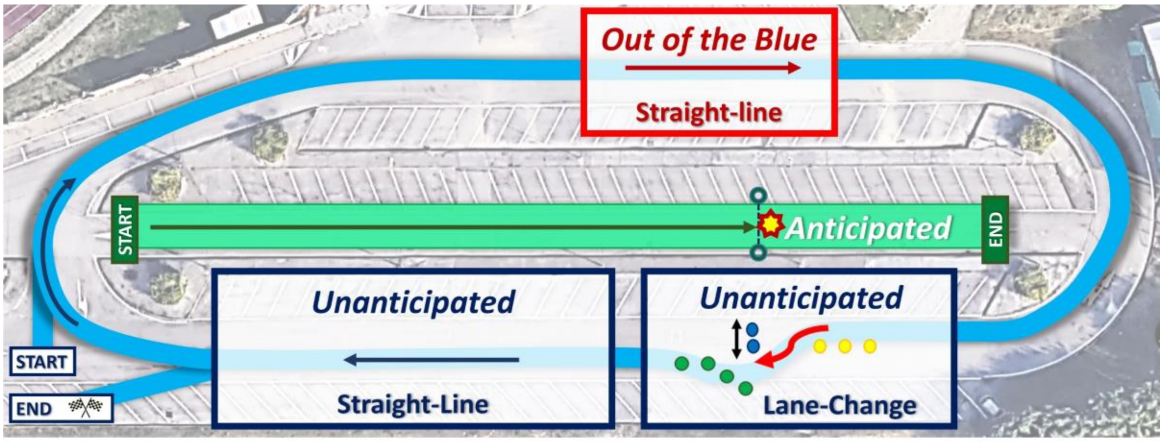

Figure A8 –Test-track with different areas of AB interventions: green for anticipated, blue for *unanticipated* and red for the intended unexpected (*Out of the Blue*)

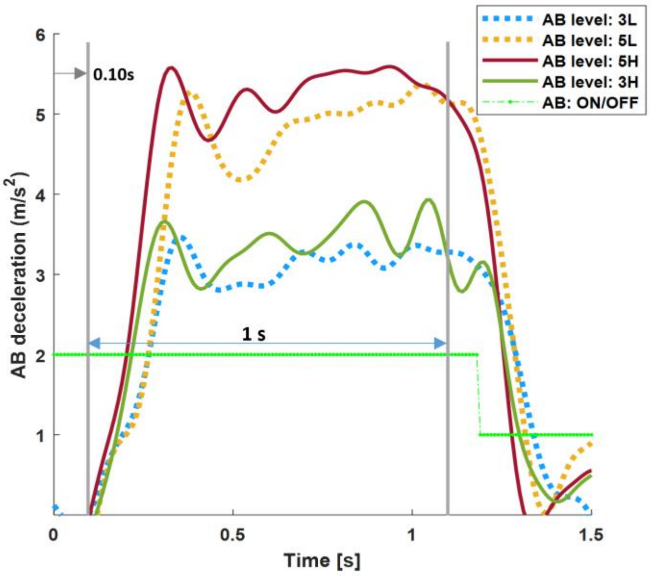

Figure A9 - Deceleration profiles of AB intervention. Latency of the AB system: 0.10s.
3L nominal level: 3m/s2 and Lower jerk (15m/s3); 5L nominal level: 5m/s2 and Lower jerk (15m/s3);
5H nominal level: 5m/s2 and Highest jerk (25m/s3); 3H nominal level: 3m/s2 and Highest jerk (18m/s3).

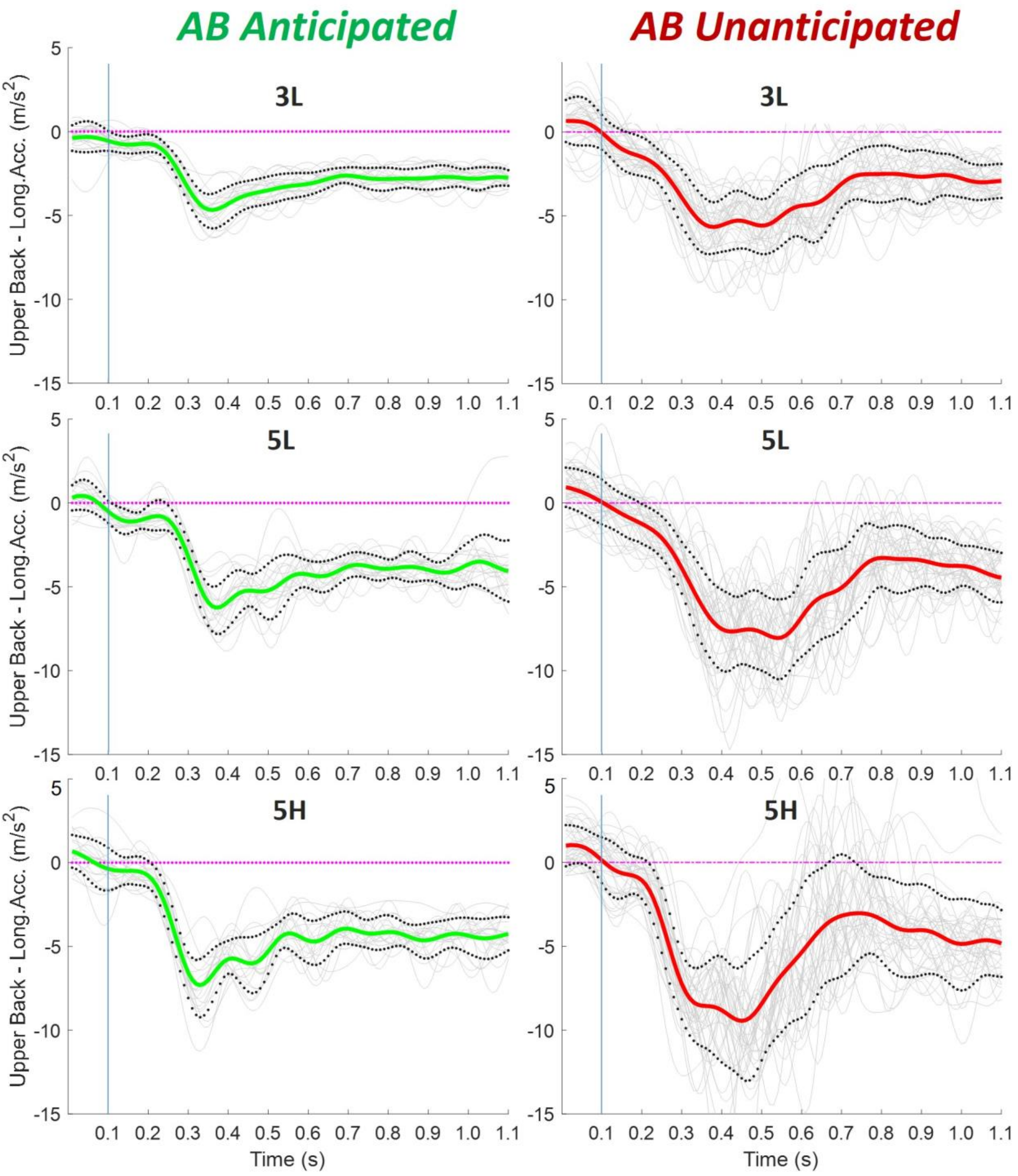

Figure A10. Acceleration of upper-body for tests with AB-Anticipated (N=20) vs. AB-Unanticipated (N=40). Thick solid lines are the average acceleration profile over participants, dotted lines are the ±1SD corridor in each instant and grey lines are the totality of observed responses per AB level and condition. Normalized time '0s' corresponds to the AB trigger onset and the vertical line at 0.1s represents the response latency of the system.

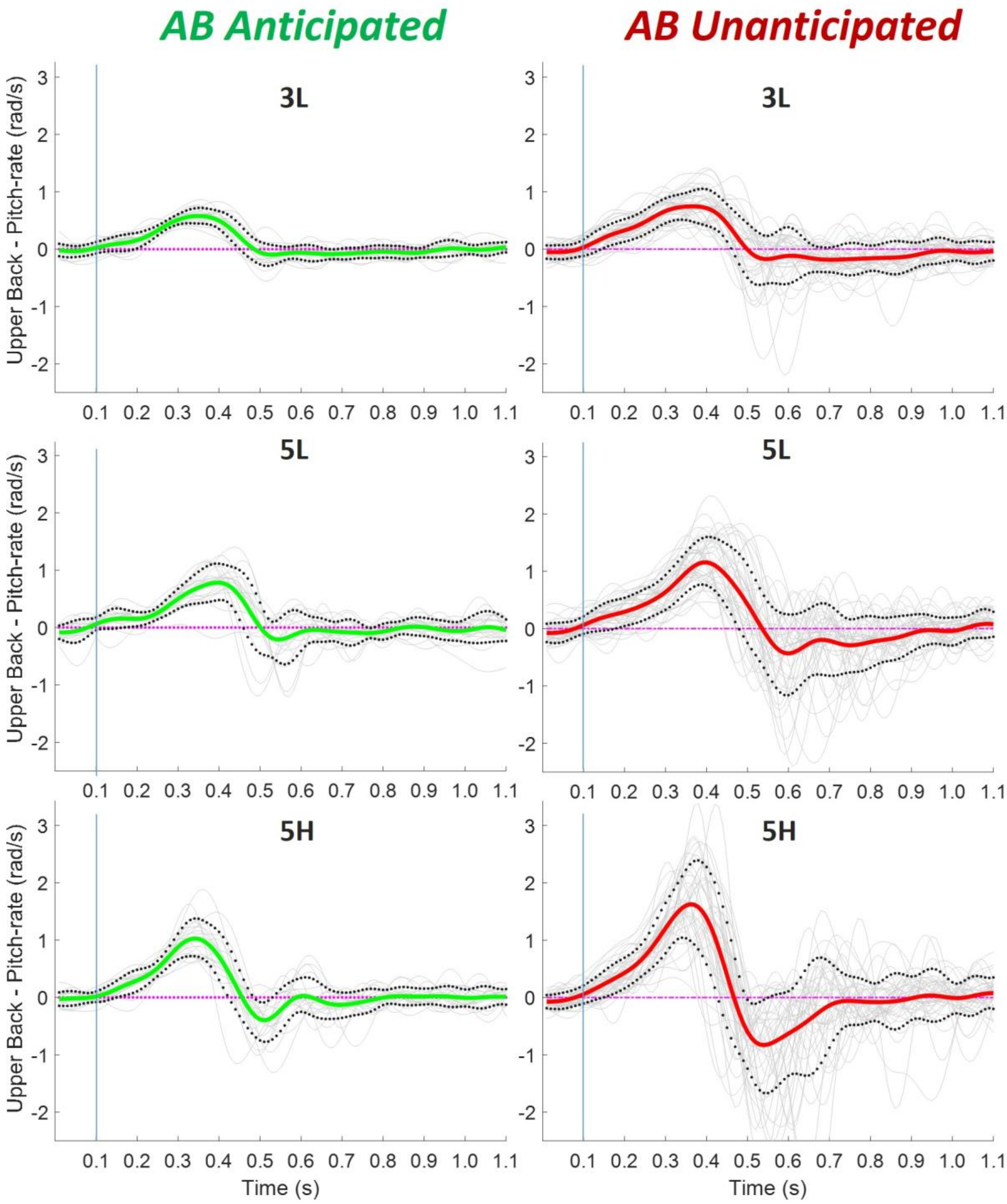

Figure A11. Pitch-rate of upper-body with AB-Anticipated (N=20) vs. AB-Unanticipated (N=40). Thick solid lines are the average pitch-rate profile over participants, dotted lines are the ±1SD corridor in each instant and grey lines are the totality of observed responses per AB level and condition. Normalized time 0 corresponds to the AB trigger onset and the vertical line at 0.1s represents the response latency of the system. Positive pitch rate represents forward rotation.

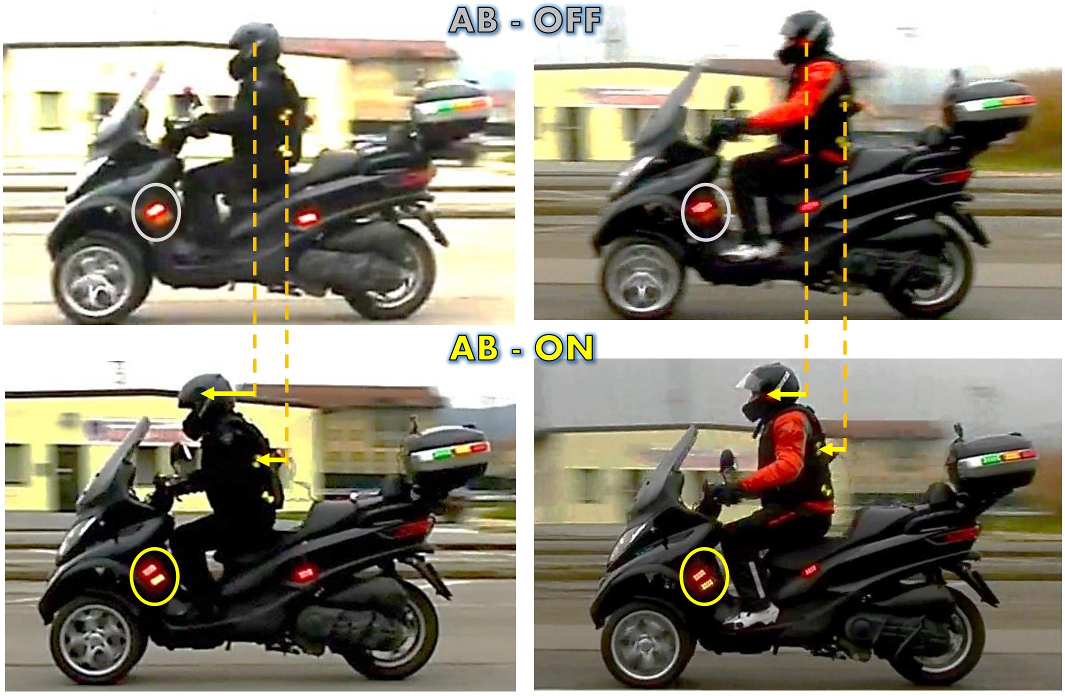

Figure A12. Examples of the position of the rider with reactive response for two cases with unanticipated activations of 5H level (5m/s2 and nominal jerk of 25m/s3). The images of the top (AB- OFF) represent the instant before the AB activation. The images of the bottom (AB – ON) represent the position during the AB activation with the rider's body displaced and rotated forward.

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