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Does ABS ensure good performance in emergency braking for less skilled motorcyclists?

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ABSTRACT

This study aims to investigate whether motorcyclists are able to use the full potential of anti-lock braking systems (ABS) in demanding braking situations that maintain the natural coupling of action and perception of emergency events, or whether instead the lack of braking skills in riders makes ABS almost ineffective and comparable to non-ABS brakes on dry pavement. Six experienced riders performed two experimental tests. First test included 12 emergency braking trials in a realistic scenario using a mock-up of an intersection conflict with a car initiating a left turn manoeuvre across the path (LTAP) of a motorcycle approaching from the opposite direction as an unpredicted moving hazard. Second test included three trials in a planned self-timed hard braking. The speed at the onset of braking was 35–45 km/h. The braking performance was measured from the initiation of brake pressure until the full stop of the vehicle. Front wheel ABS usage was determined by the pressure in the master cylinder and wheel callipers. The testing resulted in 85 data runs with full stop braking manoeuvres.

Results revealed four categories of riders classified by their front wheel ABS usage during the emergency braking tests, which included two riders who underused front wheel ABS (9.6% and 27.4% of braking time on average). The worst case resulted in a significantly longer braking distance (braking deceleration of 5.2 m/s^2). The highest skilled rider, who reached initial jerks close to 30 m/s^3, used the ABS of the front wheel 93.7% of the braking time on average, resulting in a braking deceleration of 7.71 m/s^2. Overall, the best braking performance was achieved in trials where the front ABS was activated for more than 80% of the braking. In planned self-timed hard braking test, where riders have more time to plan the braking manoeuvre, the experience rider with lowest performance during the emergency braking test improved braking efficiency and was able to increase ABS activation from 9.6% to 26.8% of the time, achieving a deceleration of 6.24 m/s^2.

ABS is demonstrated to reduce stopping distances and to improve stability under all braking conditions, but such features are not enough to guarantee a good braking performance in emergency events if the riders have not the skills to utilize the full braking power of the motorcycle. Less skilled riders, even with ABS, may not have the confidence to increase braking power further when reaching high decelerations that push them to the limit of their stabilisation control in emergency braking, thus increasing braking distance with potentially life-threatening consequences. Our results suggest that many experience riders still need knowledge and skill to make the ABS work to its optimum in emergency events to avoid crashes. Further research with larger sample sizes including the full diversity of the motorcyclist population is recommended to determine the actual proportion of motorcyclists underusing ABS.

1. Introduction

Motorcycles are a flexible and sustainable means of transport. However, motorcycle crashes claim more lives worldwide than any other mode of transport (WHO, 2018). To reduce crashes three main ways have been identified to achieve safety improvements: infrastructure (safer road infrastructure), in-vehicle safety systems (safer vehicles with advanced technology) and road user education/training.

Emergency braking is the most frequently used crash avoidance manoeuvre when riding a motorcycle (ACEM, 2009; Hurt et al., 1981). According to the results of in-depth studies and accident reconstruction analyses, systems such as anti-lock braking systems (ABS) can drastically reduce the likelihood of a motorcycle rider being involved in a fatal crash (Fildes et al., 2015; Rizzi et al., 2015; Teoh, 2011, 2022; Roll et al., 2009). ABS have been declared mandatory for new motorcycles with an engine displacement above 125 cc (cc) in some regions like European Union, Australia or India, and in USA ABS is standard on more than half of 2020 model motorcycles. ABS shortens braking distances in general, and on top of this provides stable braking characteristics on all road surfaces. However, few studies have been conducted with experimental trials on closed circuits to demonstrate that riders are able to exploit the full potential of ABS during emergency braking. Vavryn & Winkelbauer (2004) found in a study with self-initiated braking tests that both experienced and novice riders were able to improve their braking deceleration using motorcycles with ABS after an introduction to brake operation and a few minutes of exercise. The authors also concluded that correct use of ABS requires instruction. Green (2006) evaluated the performance of a rider using different motorcycles with and without ABS, and reported that ABS generally improved braking distance performance in most test conditions, whether braking on a dry or wet

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surface. More recently, in a study with two expert riders driving between 65 and 100 km/h and with self-initiated braking on dry surfaces, Dinges & Hoover (2018) reported that the braking distance obtained was similar for motorcycles with and without ABS. Other tests with emergency braking showed that less skilled riders can lose control of the vehicle when locking the front wheel of a motorcycle without ABS (Huertas-Leyva et al., 2020). In summary, previous studies suggest that ABS, if used to its full braking capacity, has the potential to reduce brake distance, and therefore motorcycle crash rates in real-life situations.

Emergency braking is also the most difficult advanced feature to learn for motorcyclists (Dewar et al., 2013), with riders involved in crashes frequently failing to perform it properly due to response time limitations precipitated by failures of detection, comprehension or control actions (Huertas-Leyva et al., 2021; Sporner & Kramlich, 2001). Previous research with naturalistic data also found that there are different categories of motorcyclists based on their preference for using the front or rear brake in similar traffic conditions (Baldanzini et al., 2016), and that despite the front brake providing most of the braking power, riders who applied only the rear brake during comfort braking still predominantly used the rear brake for hard braking (Huertas-Leyva, 2018).

Braking on a motorcycle is a complex task that requires the application of correctly proportioned front and rear brake pressure, appropriately adjusted for variations in vehicle stability and road friction. When braking is required to avoid a crash where there is no time to plan the manoeuvre or panic occurs, its execution must be performed as part of an automatic behaviour. For this reason, it is critical to have technology capable of improving braking performance, as well as the knowledge and ability of riders to use such technology appropriately in response to emergency situations. From the literature, the scenario where specific braking skills are required and with the highest risk to cause serious injuries involves an oncoming car initiating an unexpected Left Turn Across the Path (LTAP) of a motorcycle (Huertas-Leyva et al., 2021) mostly due to failure to yield to motorcyclists at intersections (Clarke et al., 2007). This type of crash was also identified as one in which ABS can reduce collision risk to a greater extent (Fowler et al., 2016).

This study aims to investigate whether motorcyclists are able to use the full potential of ABS in demanding braking situations that maintain the natural coupling of action and perception of emergency events, or whether instead the lack of braking skills makes ABS almost ineffective and comparable to non-ABS brakes on dry pavement. To this end, this study developed a test in a controlled LTAP scenario that required riders to predict whether a car would cross their path and respond by braking in the shortest possible distance without prior preparation as in real emergency braking events. Additionally, as a secondary objective we want to understand whether the braking efficiency of a motorcyclist in a task requiring a perception-action process, such as the task designed to simulate emergency braking, is lower than the efficiency demonstrated in a less complex task represented by a hard braking test with programmed initiation (representing a typical test to measure braking performance).

2. Materials and methods

2.1. Participants

Six experienced motorcyclists who were regular riders of large-displacement motorcycles were selected as volunteers. The participants were recruited among employees of the University of Florence by posting advertisements and sending emails to university mailing lists. The requirements for the selection were to have experience riding a high engine motorcycle (>500 cc), and to regularly ride a motorcycle in the last 10 years (minimum once per week). Due to the fact that the test motorcycle was large, heavy and powerful, inexperienced riders were not considered for safety reasons. Participants were male with a mean ± SD age of 45.7±6.6 years and height of 178.3±6.2 cm (Fig. 1). Approval was granted by an institutional human research ethics committee. All participants gave their informed written consent to participate in the experiment.

2.2. Vehicle and instrumentation

The model of motorcycle tested for the experiments was a large engine capacity touring motorcycle (model Ducati Multistrada 1200 Enduro) with 1200 cc, 152 horsepower and weighing 225 kg. The motorcycle was equipped with a 2x320 mm semi-floating disc front brake with 4-piston calipers and ABS and a 265 mm disc rear brake, 2-piston with floating calliper and ABS. The brakes of the motorcycle are independently actuated by right hand lever (front brake) and right pedal (rear brake). Furthermore, combined braking system (CBS) was triggered when using single front brake. The motorcycle's electronic control unit (ECU) could be set to four different modes (Sport, Touring, Urban, Enduro). The riding mode selected for the tests was Urban, that meant that: power output of the motorcycle was restricted to 100 hp; traction control was at high levels; ABS was at level 3 which offered more safety by letting the wheel slip less and included rear-lift detection and front/rear combined braking. A set of braking tests on dry pavement with an expert rider to characterise the braking power of the motorcycle revealed that the braking power of the rear brake alone would barely reach 50% of the maximum deceleration that could be achieved by applying both brakes. In contrast, the front brake alone would achieve approximately 82% of the maximum deceleration.

Data from the ECU, including brake pressure at the front and rear wheel, front brake pressure of the master cylinder, front and rear wheel speed, vehicle speed and longitudinal acceleration, were sent via CAN bus to an on-board data acquisition system. The sampling frequency was 100 Hz. The rear brake pressure of the master cylinder was not registered but it was assumed that it did not add significant information considering that the main braking power of the motorcycle came from the front brake and that the ABS of the rear wheel can be easily activated without reaching high decelerations. Therefore, this study focuses on the use of the front ABS, as its correct use is decisive in achieving maximum deceleration.

Additionally, rider response and visual stimuli leading to emergency braking were examined using two high-speed video cameras. One camera was positioned at the front of the motorcycle to record the precise onset of car turn initiation. The second camera was positioned pointing at the rider to register the head movements. Furthermore, the side view of the interaction between the motorcycle and the car was recorded with a video camera on a tripod.

2.3. ABS function

Anti-lock braking systems (ABS) are designed to prevent the wheels of the vehicle from locking, to shorten the braking distance and to enhance riding stability. ABS is managed by the ECU, which computes wheel slip ratio values using information from the wheel speed sensors and the vehicle's reference speed. When the pressure applied by the rider on the brake lever or pedal causes the wheel to exceed the reference slip ratio values, the ABS control valve will either block the brake line, isolating the brake from the master cylinder (MC) to limit the pressure, or release some of the brake pressure at the wheel, thus preventing wheel lockup and maximising the frictional force between the road and the tires. As soon as the wheel returns to the reference slip ratio values, provided that the rider continues to exert pressure on the brake, the braking pressure on that wheel will continue to be increased by pulsing.

Fig. 2 shows an example of ABS activation, where it can be seen how the braking pressure of the master cylinder (MC) is regulated by the ABS valve to avoid the risk of wheel lock-up, so that the braking pressure on the wheel is limited or released when the ABS sensors detect that the

Fig. 1. Test motorcycle with the participants of the study.

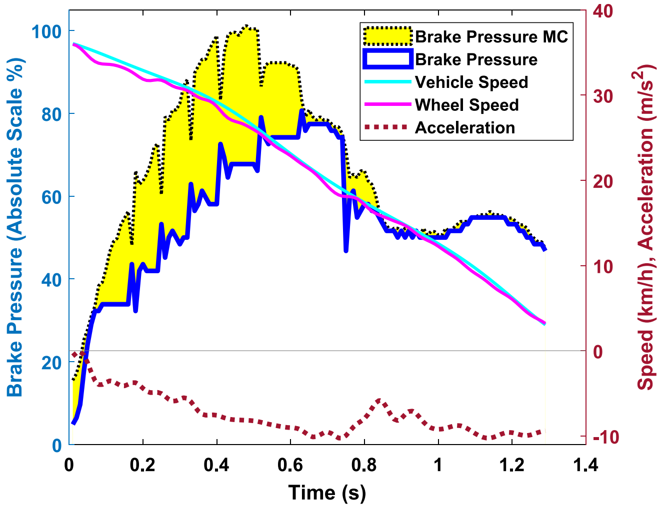

Fig. 2. Brake Front MC is the actual front brake pressure on the master cylinder. a) Brake pressure during braking test.

wheel is slipping or that the braking pressure gradient is too high.

2.4. Experimental procedure

The study included two types of experimental tests (see Table 1). The first test consisted of a series of 12 emergency braking trials with an opponent vehicle (passenger car) in a stimulus-response scenario. In the second test, subjects performed three trials of self-initiated hard braking.

This study followed the experiment procedure defined in Huertas-Leyva et al. (2019), where more details can be found, which was used to measure the braking skills of the riders on high engine scooter without ABS. The test was conducted in an enclosed car park with a 90 m × 20 m test area with dry asphalt in good condition and in broad daylight.

2.4.1. Emergency braking test at an intersection

The scenario selected for the emergency test was an oncoming car initiating an unexpected left turn across the path of a motorcycle (Left Turn Across Path/Opposing Directions – LTAP/OD). The test scenario was designed using existing lane markings along with traffic poles and cones to create an experimental scenario that mimics a non-controlled intersection. Fig. 3 shows how the intersection allows an oncoming car to either continue straight across the intersection or turn left across the path of the motorcycle. The car was driven by one of the experimenters who had extensive experience developed in this type of test.

Table 1
Description of the test phases during the experimental procedure.

Protocol Phases	Time/ Trials	Description
Pre-Test Phase	≥10 min	Environment and PTW Familiarization
Practice trials	7 trials	One or two repetitions per condition TN, TI, SN, SI
Emergency braking tests with LTAP scenario:		Six repetitions per each of the four conditions:
- 1st session	8 trials	- TN: car Turns with No indicator (6 braking trials)
- 2nd session	8 trials	- TI: car Turns with Indicator (6 braking trials)
- 3rd session	8 trials	- SN: car goes Straight with No indicator (6 nonbraking trials) - SI: car goes Straight with Indicator (6 nonbraking trials) Total: 24 trials including 12 emergency braking trials
Self-initiated hard braking tests	3 trials	Hard braking when reaching a virtual line delimited by cones (no opponent vehicle)

Motorcycle and car started from stationary positions at opposite ends of the experimental area. After a visual “go” signal, both vehicles drove to the intersection. In each trial, the car approached the intersection at a speed of 30 km/h and could either continue straight ahead or initiate a left turn across the path of the motorcycle. In addition, a mental load factor was placed on the participant, as the car could either put on the indicator or not regardless of the chosen trajectory. Each of the four conditions (TN: car Turning with No-indicator; TI: car Turning with Indicator; SN: car going Straight with No-indicator; SI: car going Straight despite having Indicator on) was repeated six times over 24 trials, which were divided into three sessions of eight trials each. The four conditions were set in a pseudo-randomised and counterbalanced manner. Therefore, during the experimental sessions, the participants had to perform 12 emergency braking trials when the car was turning in front of them (TN and TI conditions).

Participants were instructed to reach speeds of 40–45 km/h when approaching the intersection and to make a response (brake or continue straight ahead) depending on the perceived stimulus of the oncoming car. Specifically, participants were instructed to brake as fast and hard as possible (as in an emergency situation) only if they perceived that the car was going to turn across their path, regardless of whether the turning

Fig. 3. a) Schematic view of the mock intersection; (b) Trial with car initiating a LTAP/OD manoeuvre.

indicator was on or off. Both vehicles then returned to their starting positions to await the "go" signal for a new trial. Trials where it was observed that either the speed reached was insufficient or that the synchronisation between vehicles to reach the intersection was considered inadequate for the purposes of the experiment were repeated at the end of the third session (up to a maximum of four), thus adding these additional trials to the eight planned.

2.4.2. Self-initiated hard braking with no opponent vehicle

After the three emergency braking sessions, volunteers conducted three self-initiated hard braking in a straight line without an opposing vehicle. Riders were instructed to reach 45 km/h and brake as hard as possible upon reaching a virtual line indicated by traffic cones placed on both sides of the road lane. This line was used as a reference for the participants, as the braking distance was measured from the onset of the brake activation until the motorcycle came to a complete stop. This braking test was done in the absence of any potential hazard, so the rider was free to start braking at his/her own decision.

2.5. Braking parameters as measures of braking performance

The onset of the braking period ($Brake_{ini}$) was determined as the instant at which the pressure applied to the front or rear brake exceeded a threshold of 2 bar with negative longitudinal acceleration. We identified 2 bars as the threshold that indicated when the rider was intentionally and deliberately using the brakes to avoid a collision when the opposing car was actually turning (in contrast to lower pressures which could be anticipatory without necessarily resulting in an evasive braking action and which did not effectively reduce wheel speed). To avoid the inclusion of speed oscillations at the end of braking, the end of the braking manoeuvre ($Stop_{PTW}$) was considered as the moment when the wheel speed fell below 3 km/h.

In this study we computed the ABS usage (ABS_{ON}) by measuring the percentage of the braking time that the pressure of the Master Cylinder (Brake Pressure MC) was higher than the brake pressure at the front wheels.

The study also used as descriptor of the braking performance the average of the braking pressure on the rear and front wheel during the braking event ($RBrake_{avg}$ and $FBrake_{avg}$) as well as the maximum ($RBrake_{peak}$, $FBrake_{peak}$) which were computed as the 95th percentile. Since the units of pressure registered depends on the type of brakes, we used a relative scale taking the maximum pressure registered in each brake sensor as reference. Thus, a value of 100% will represent the maximum braking pressure that was possible to apply.

The braking distance (d_B) was measured by integrating the motorcycle speed time series $v(t)$ during the braking period:

$$d_B = \int_{Brake_{ini}}^{Stop_{PTW}} v(t)dt \tag{2}$$

in discrete form becomes

$$d_B = \sum_{j=1}^{n-1} \frac{v_j}{T_s} \tag{3}$$

where n is the number of samples in the braking period, T_s the sample rate (0.01 s) and v_j is the motorcycle speed in the instant j.

The longitudinal acceleration (a_{long}) was computed from the differential of the speed data (4).

$$a_{long}(t) = \frac{d}{dt}v(t) \tag{4}$$

In discrete form (4) becomes

$$a_{long}[n] = \frac{v_n - v_{n-1}}{T_s} \tag{5}$$

Peak deceleration (dec_{peak}) and effective deceleration ($dec_{effective}$) values were used to evaluate rider performance with comparisons across trials and subjects. The dec_{peak} was computed as the 95th percentile of the longitudinal deceleration (dec_{long}) time series as a more robust value than the absolute maximum deceleration. The effective deceleration ($dec_{effective}$) was computed using the braking distance (d_B) and the difference between final velocity at stop ($v_f \approx 3$ km/h) and velocity at braking initiation (v_i) (Eq. (6)). This measure provides an accurate assessment of the rider's actual braking performance in a given trial because it relates directly to total braking distance.

$$dec_{effective} = -\frac{\left(v_f{}^2 - v_i{}^2\right)}{2{*}d_B} \tag{6}$$

In addition, the initial jerk ($jerk_{ini}$) was determined as the average jerk in the interval comprised between the start of the braking manoeuvre (t_1) and the instant when the deceleration reaches 4.5 m/s^2 (t_2) (Eq. (7)).

The value of 4.5 m/s^2 was selected to assure a maximum deceleration that all the participants could achieve during the first phase of braking.

$$jerk_{ini} = \frac{4.5m/s^2}{t_2 - t_1} \tag{7}$$

2.6. Data analysis

To assess between-subject differences in the use of the ABS brake on the front wheel, we performed analysis of variance with the dependent variable *ABS ON* and with Rider as a fixed factor, followed by a post-hoc analysis to determine which riders were significantly different from each other in braking technique. We applied Welch's ANOVA when homogeneity of variance between groups was not met (Delacre et al., 2020). The classification of the participants into different ABS usage profiles was done based on the groups defined in the post-hoc analysis. A descriptive analysis of the features related to braking performance was conducted by grouping each of the identified profiles. Additionally, an analysis of variance was performed with each feature to see the influence of ABS usage on braking performance (using the ABS usage profile as a fixed factor). A Pearson correlation coefficient was computed to determine the relationship between the use of the brakes (ABS usage and average pressure of both front and rear brakes) and the effective deceleration achieved. Learning or fatigue effect between sessions was explored with analysis of the variance to assess whether the ABS usage among riders or braking performance experienced any significant change.

Finally, to analyse the effect of the type of braking test (i.e., emergency vs. self-initiated) on rider behaviour, we performed a descriptive analysis of the braking descriptors by type of ABS usage profile. For this comparison, the sample of emergency braking trials corresponded to the last three braking trials of each participant. In this way, the two samples compared were balanced and possible biases caused by learning or fatigue between sessions were avoided. For all the analysis the statistical significance was set a priori at 0.05. For the multiple pairwise comparisons of the post-hoc analysis we set an uncorrected significant level of 0.05/[number of comparisons] to apply a Bonferroni-adjustment equivalent to alpha 0.05.

3. Results

3.1. Emergency braking test

A total of 70 emergency braking tests were collected, corresponding to 11 or 12 tests per subject split over three sessions. The average initial speed before starting to brake was 41.6 km/h (SD = 5.9).

3.1.1. Effect of different uses of ABS on braking performance

Before proceeding with the analysis of the variance we tested the assumption of normality and homogeneity of variances. The test for normality, examining the Shapiro-Wilks test, indicated the data for the groups of variables of the analysis were statistically normal. The Levene's F test revealed that the homogeneity of variance assumption between groups was not met in most of the cases because highest and least skill riders performing the test were more consistent than those intermediate that were trying different approaches with a higher variance in their performance. Thus, Welch's ANOVA and Games-Howell post hoc procedure was used instead of classical one-way ANOVA. The Welch's ANOVA showed significant main effect for rider factor on ABS usage (F (5, 28.69) = 216.94, p <.001,), i.e. different riders made different use of front wheel ABS. Post-hoc Games-Howell's test for multiple comparisons (alpha set at 0.05) identified four profiles associated with one or more riders in which the mean values of ABS usage differed significantly (Fig. 4).

Two of the identified profiles showed riders under-using the front wheel ABS, one significantly to the point of hardly using it at all (subset *A-Minimum* ABS usage; M = 9.6%, SD = 8.0) and one moderately (subset *B – Partial* ABS usage; M = 27.4%, SD = 6.0). The other two profiles showed riders activating ABS during most of the braking, one profile for more than 2/3 of the braking (subset *C – Substantial* ABS usage; M = 67.8%, SD = 22.1) and the other with ABS activated almost from the beginning to the end of the braking (subset *D – Maximum* ABS usage; M = 93.7%, SD = 5.6).

Fig. 5 and Fig. 6 show the usage of brakes during a typical test for each of the subjects, including the brake pressure of the master cylinder and the brake pressure on the front wheels. The Video 1 from the Supplementary material shows examples of the braking trial for riders with different profiles.

Table 2 lists the means and standard deviations (SD) for the braking descriptors and the Welch's ANOVA results with post-hoc Games-Howell test for the four ABS usage profiles that have been identified. The effect of the rider profile of ABS usage was significant (p <.001) in all the parameters analysed. Table A1 of the Appendix B shows the statistics of the results. The significant level for multiple comparison with Games-Howell test was set to 0.008 [0.05/6 pairwise comparisons] and 0.001 [0.05/(6 pairwise comparisons * 8 variables)] to have a Bonferroni-adjusted alpha level of 0.05. Pearson correlations between the features and the deceleration are presented in Table A2 of Appendix-B.

The Welch's ANOVA revealed that to a greater or lesser extent the type of ABS usage profile significantly affects each of the descriptors of braking performance. The Games-Howell's post-hoc test (*alpha* set at 0.01) for features $FBrake_{peak}$, $FBrake_{avg}$, and dec_{peak}, $dec_{effective}$ identified

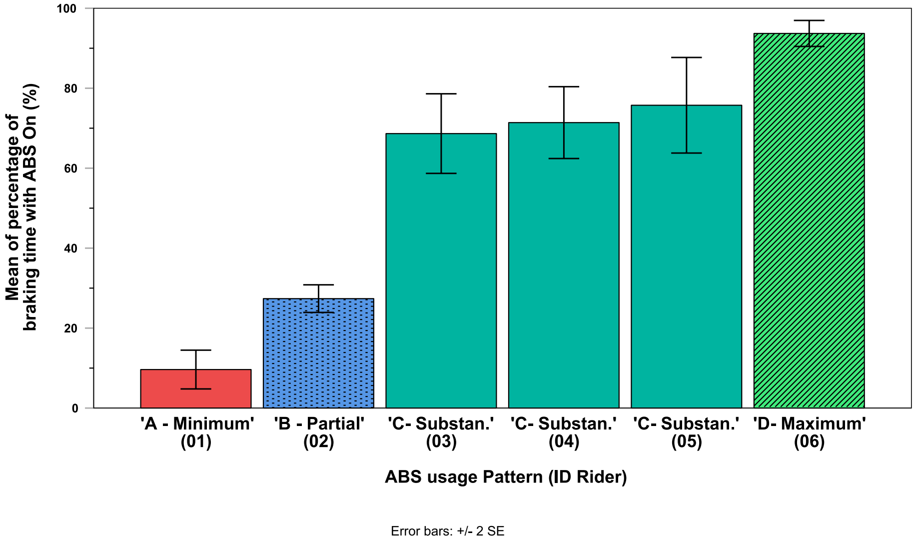

Fig. 4. Average values for each rider during the test sessions. A, B, C and D represents the identified profile for each rider.

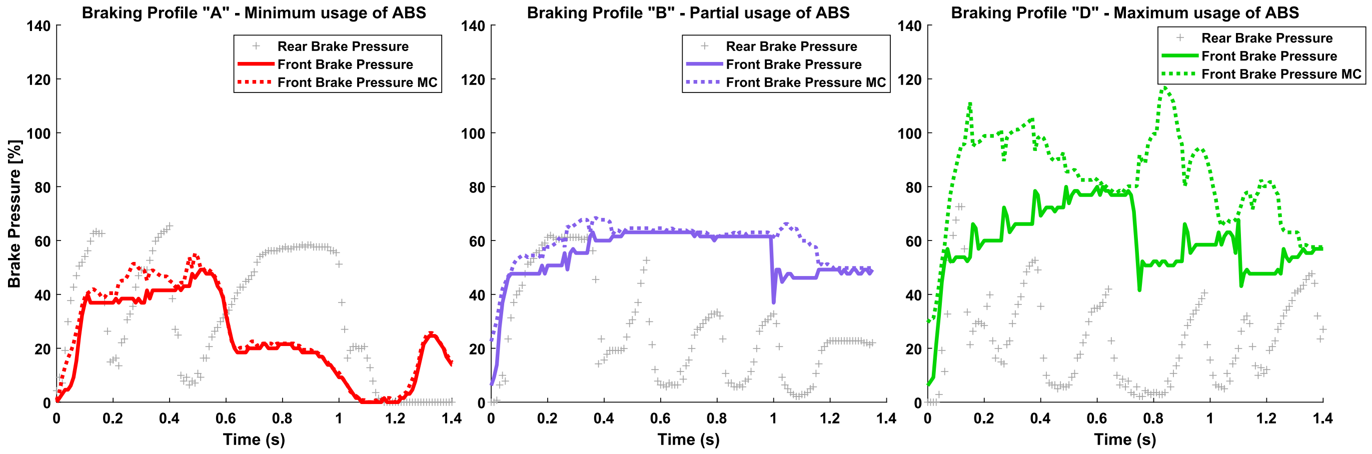

Fig. 5. Examples of brake pressure during pseudo-emergency braking from left to right: Rider profile ‘A- Minimum’ (minimum use of ABS/suboptimal performance); rider profile ‘B- Partial’ (insufficient use of ABS/suboptimal performance); Rider profile ‘4- Maximum’ (Maximum use of ABS) with best performance with high initial brake gradient.

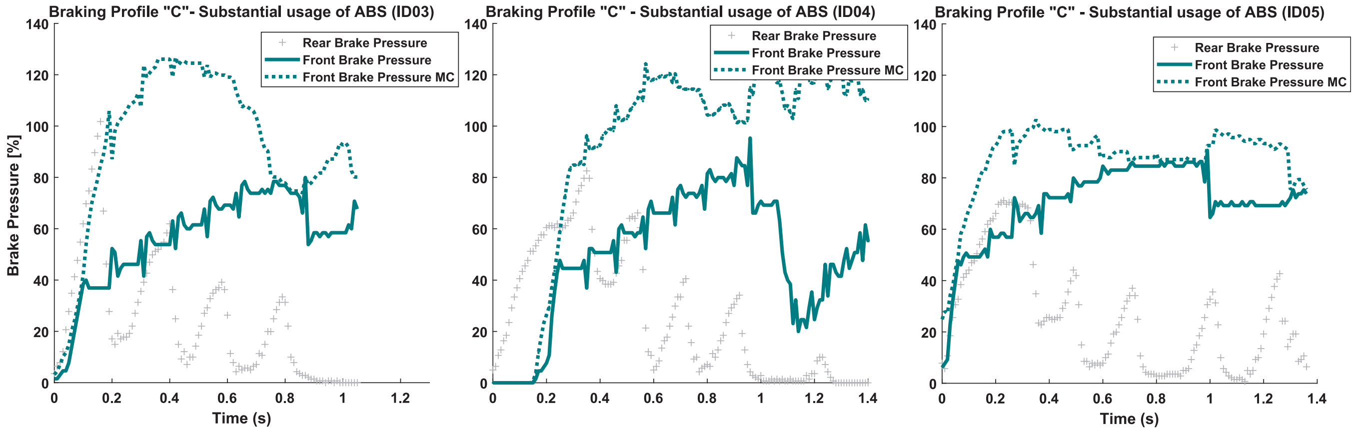

Fig. 6. Riders with profile ‘C-Substantial’ pushing the brakes hard enough to activate the ABS for a fair amount of time and get good braking performance without getting the best braking performance.

Table 2
Mean and Std. Deviation (SD) by Patterns of ABS usage. Welch’s ANOVA and pairwise comparison results. * p <.008, ** p <.001.

	A: Minimum n = 11	B: Partial n = 12	C: Substantial n = 35	D: Maximum n = 12	Welch ANOVA	Games-Howell Comparison					
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	*p*	A vs B	A vs C	A vs D	B vs C	B vs D	C vs D
ABS ON (%)	$9.64^{(1)}$ (8.0)	$27.37^{(2)}$ (6.0)	$67.77^{(3)}$ (22.1)	$93.70^{(4)}$ (5.6)	<0.001	**	**	**	**	**	**
Decel eff (m/s^2)	$5.20^{(1)}$ (0.6)	$6.80^{(2)}$ (0.4)	$6.69^{(2)}$ (0.7)	$7.71^{(3)}$ (0.2)	<0.001	**	**	**	NS	**	**
Decel peak (m/s^2)	$7.52^{(1)}$ (0.6)	$8.84^{(2)}$ (0.6)	$9.76^{(3)}$ (0.4)	$9.72^{(3)}$ (0.3)	<0.001	**	**	**	*	*	NS
Jerk ini (m/s^3)	$19.2^{(1)}$ (6.3)	$24.2^{(1)}$ (3.6)	$19.4^{(1)}$ (6.3)	$29.0^{(2)}$ (2.6)	<0.001	NS	NS	*	NS	*	**
FBrake avg (%)	$20.32^{(1)}$ (4.2)	$50.92^{(2)}$ (5.9)	$56.16^{(2,3)}$ (8.4)	$61.50^{(3)}$ (3.1)	<0.001	**	**	**	NS	**	NS
FBrake peak (%)	$39.15^{(1)}$ (6.6)	$60.61^{(2)}$ (5.3)	$83.37^{(3)}$ (6.1)	$84.38^{(3)}$ (5.5)	<0.001	**	**	**	**	**	NS
RBrake avg (%)	$31.33^{(2)}$ (2.3)	$28.48^{(2)}$ (3.8)	$24.92^{(1,\ 2)}$ (4.1)	$21.41^{(1)}$ (3.2)	<0.001	NS	NS	**	NS	**	NS
RBrake peak (%)	$62.19^{(1,2)}$ (7.8)	$55.53^{(1)}$ (5.4)	$68.41^{(2)}$ (9.5)	$56.61^{(1)}$ (8.3)	<0.001	NS	NS	NS	**	NS	* (0.002)

$^{(i)}$ subset membership *i*, for *i* = *1, 2, 3* or *4* from the Games-Howell’s post-hoc tests.

three subsets differing significantly among them, where in each variable the profiles *Minimum*, *Partial* and *Maximum* usage of ABS were identified in different subsets (subset 1 for *Minimum* ABS usage, subset 2 for *Partial* ABS usage, and subset 3 for *Maximum* ABS usage). The profile *Substantial* usage of ABS was classified between subset 2 and subset 3. Both the peak front brake pressure and peak deceleration ($FBrake_{peak}$, dec_{peak}) of the *Substantial* profile were similar to those of the rider with *Maximum* usage of ABS. However, the deceleration $dec_{effective}$ achieved in the *Substantial* profile was significantly lower than the deceleration achieved by the rider with the profile “*Maximum* usage of front ABS”. It should be noted that the differences in ABS usage between profile *Partial* and profile *Substantial*, contrary to expectations, did not affect the effective braking deceleration and both profiles showed a similar response (M = 6.80 m/s^2 SD = 0.43 and M = 6.69 m/s^2 SD = 0.69 respectively). The worst braking performance (average $dec_{effective}$ = 5.20 m/s^2) was achieved by the rider with profile *A* with *Minimum* use of ABS, which at 50 km/h would represent a braking distance 6 m longer than that of the rider with profile *D* who with *Maximum* use of ABS achieved an average effective deceleration of 7.71 m/s^2.

Regarding the initial jerk feature, in spite of which the Games-Howell test only found significant differences between the rider with *Maximum* profile (average of 29.0±2.6 m/s^3) and the others, it is remarkable that the average initial jerk of the rider with *Partial* usage of ABS was higher than the average of the riders of *Substantial* profile. This higher initial jerk by the rider with *Partial* profile may have compensated for the noted under-utilisation of the front wheel ABS, resulting in an acceptable/fair braking performance.

The effect of type of profile of front brake's ABS usage was also significant on variables $RBrake_{avg}$ ($p < .001$) and $RBrake_{peak}$ ($p < .001$). There was a trend among the riders that used less the front ABS to apply higher pressure on the rear brake, that above certain thresholds (about 20% of the maximum) did not improve the performance because the rear wheel started to locked-up. This observed trend is supported by the weak negative correlation found between $RBrake_{avg}$ and effective deceleration ($r(68) = -0.428$, $p < .001$). Rear wheel ABS was triggered with lower braking pressure (i.e., more easily), so in practically all braking tests the riders activated the rear brake ABS and, unlike what we observed with the front brake, the small differences in rear brake usage found had negligible impacts on braking performance.

3.1.2. *Association between front wheel ABS usage and deceleration*

A Pearson correlation coefficient was computed to assess the relationship between the ABS usage during the emergency braking test and effective deceleration. Overall, there was a positive correlation between the two variables, $r(68) = 0.676$, $p < .001$. Increases in use of front wheel ABS were correlated with increases in effective deceleration. A scatterplot summarising the results of Fig. 7 reveals the following insights:

- There is a linear association between ABS usage on the front wheel and braking deceleration in the range 0–40% of ABS on. A significant regression equation was found ($F(1, 26) = 36.69$, $p < .001$), with an R^2 of 0.585. For the range of 0–40% of ABS on, the predicted $dec_{effective}$ is equal to 4.76 m/s^2 + 0.065(ABS on) m/s^2 when ABS_on is measured in %. Effective braking deceleration in the test increased 0.65 m/s^2 for each 10% of ABS_{ON} for the range 0–40% ABS_{ON}.
- During the emergency braking test, if ABS was on for less than 15% of the braking duration, the result was poor braking performance with an effective deceleration below 6 m/s^2 (profile *A* cases).
- When ABS was activated between 15% and 80%, good performance was achieved (between 6.0 and 7.5 m/s^2), with a few outliers which were typically related to low initial jerk.
- The best braking performance (above 7.5 m/s^2) is achieved almost exclusively when ABS usage is higher than 80% (profile *D* cases).

3.1.3. *Learning or fatigue effect by session*

For the analysis of learning or fatigue effect, we performed a one-way ANOVA test, as in this case the assumptions of normality and homogeneity of variances between groups were met. The session factor had no significant effect on *ABS usage* ($F(2, 68) = 0.344$, $p = .710$), suggesting that there was no learning or fatigue effect during testing that modified ABS usage among riders. However, fatigue symptoms were detected in rider of *B – Partial* profile in the 3rd session, where effective deceleration decreased ($F(2, 9) = 4.574$, $p = .043$) compared to the average of the two preceding sessions (M = 6.46, SD = 0.39 vs. M = 7.04, SD = 0.28) and peak deceleration also decreased ($F(2, 9) = 22.297$, $p < .001$) dropping from an average of 9.4 m/s^2 in the first session to 8.2 m/s^2 in the last

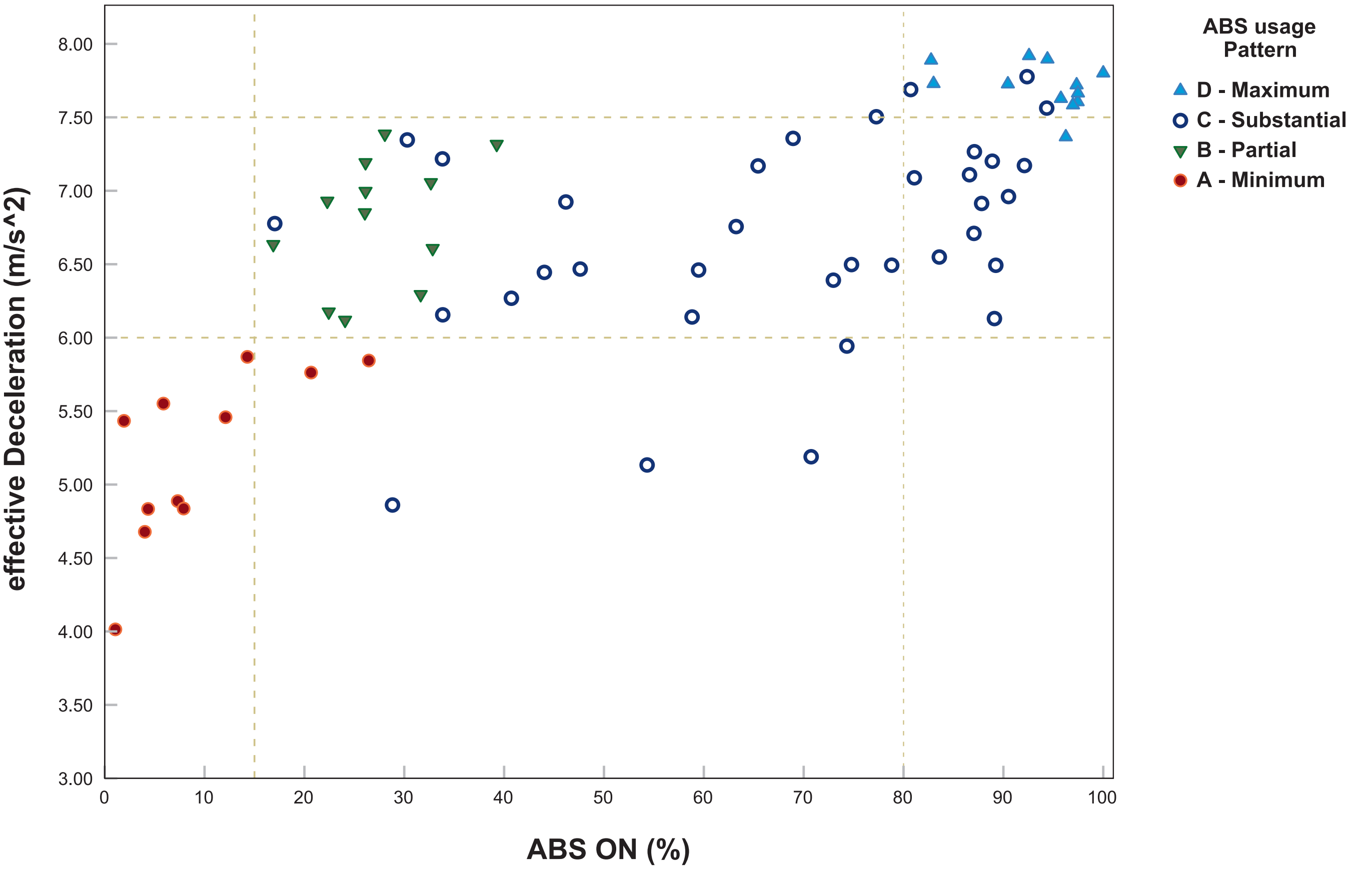

Fig. 7. Scatter plot showing ABS usage association with braking deceleration. Dotted lines represent the thresholds identified.

session.

3.2. *Emergency test vs. self-initiated hard braking*

The results from self-initiated hard braking tests were compared with those of the emergency braking test designed to assess whether there were differences indicating a change in rider behaviour (Table 3). Data from self-initiated braking tests were analysed for five participants, since rider identified as *B – Partial* profile was excluded of this test due to the fatigue signs perceived at the end of the emergency braking tests. A descriptive analysis of the braking parameters showed little difference between the three last emergency braking trials in response to a perceived dynamic hazard and the three self-initiated hard braking trials for the riders with *Maximum* and *Substantial* use of the ABS. In contrast, the rider who made minimal use of ABS during the emergency test (*Minimum* profile) experienced a considerable behavioural change in self-initiated braking, achieving better braking performance, as a result, among other things, of a higher use of front wheel ABS (moving from 7.3 to 27.8%). Fig. 8 shows two typical cases of the braking response of this rider where these differences can be appreciated. Unlike the response with the emergency test, when the rider had more time to prepare for braking, he was able to use the front brake with more strength, activating the ABS during the first half of the braking until a peak deceleration is reached (typically about 8 m/s^2), after which the braking intensity progressively decreases.

4. Discussion

The aim of this study was to understand whether the full benefits of ABS on motorcycle braking performance evidenced by previous studies with simulations apply to all the riders in emergency events, or whether on the contrary less skilled riders are not able to use ABS effectively not achieving high decelerations when facing a critical event. For that we designed a close to real life emergency braking test where experienced riders had to perform an emergency braking on an instrumented touring motorcycle with ABS. The study found evidence that some less skilled riders are not able to take full advantage of the ABS, operating far from the actual capabilities of the brakes of the motorcycle. Although the danger of wheel locking was known to be suppressed by ABS, two out of six subjects avoided (or were not capable of) using the full braking power of the motorcycle. In one of these cases one rider experienced more hesitant braking behaviour, resulting in clear under-braking and a poor overall deceleration result. The other rider (profile *B – Partial*) left limited braking control to ABS with under-braking behaviour (27.37% average of ABS usage). Despite this, the dry road conditions of the test and the moderate initial speed (around 45 km/h) allowed such under-braking to be compensated in terms of braking distance by a high initial jerk leading to a good overall deceleration. This result could however have been further improved by using ABS for longer with a stronger braking force. Furthermore, the braking procedure was more demanding for this rider, showing signs of fatigue in the last session of the test where the braking performance started to decrease significantly. Therefore, even if the motorcycle is equipped with powerful braking systems, riders must first of all learn to use them properly in the most demanding conditions. We observed that in dry road conditions at 50 km/h the braking response of the profile with minimum utilisation of front ABS represents a distance 6 m greater than would be achieved with maximum utilisation of ABS, a distance that could make the difference between a successful evasive manoeuvre and a crash with injury to the rider. Less skilled riders, although they may be experienced riders, may need specific training to use the full braking power of the motorcycle with confidence, otherwise some of the vehicle's safety features may be rendered useless. Among the participants, one of them managed to achieve maximum performance by activating the ABS of the front wheel from start to end (93.7% average use). This result also indicated the importance of applying a high initial jerk in emergency braking cases where the initial speed is not particularly high. Only the most skilled rider performing the test of our study was able to press firmly on the brake from the start during the emergency braking tests, reaching initial jerks close to 30 m/s^3. The initial braking response was probably related to the test conditions, where the rider had to observe the environment to detect the onset triggered by the car when turning.

The secondary objective was to determine whether the rider behaviour in the task designed to simulate emergency braking was different from the behaviour in a more standard hard braking task. The study revealed that the braking behaviour of the less skilled rider performing the test of our study changed markedly when comparing the two types of tests. This rider, classified as profile *A – Minimum* usage of ABS, who in some cases braked with so little pressure that the ABS was not activated for the entire braking time of the emergency test (ABS_{on} average of 7.3%), changed to having the ABS activated for more than a quarter of the braking time (ABS_{on} average of 26.8%). Despite this performance improvement, it was noted that the rider released the brakes shortly after the motorcycle reached deceleration peaks of around 8 m/s^2. The self-initiated braking test helped to show that the less skilled subject braking (profile A – *Minimum*) was able to activate the front wheel ABS and that the context of the emergency test where the rider has to brake without preparation lowered his performance significantly. Among the four subjects who did activate front wheel ABS most of the time (profile *C- Substantial* and *D- Maximum* ABS usage), no noticeable differences were found between the two types of tests, apart from a tendency to brake with greater initial jerk in the self-initiated braking tests.

There are some limitations to consider for the generalizability of the study's findings. The study had a small sample size and was focused on experienced riders, however, the sample size was larger than most previous studies. The few previous research with field test using ABS, with the exception of Vavryn & Winkelbauer (2004), showed run the experiments with only one or three riders in tests with self-initiated braking. Furthermore, the finding of the previous work that revealed

Table 3
Means and standard deviations (SD) of the braking features for each profile of rider detected.

ABS usage Profile	Type of Test	ABS usage (%)	Decel. effective (m/s^2)	Decel. peak (m/s^2)	Initial Jerk (m/s^3)	FBrake peak (%)	FBrake avg (%)	RBrake peak (%)	RBrake avg (%)
D – Maximum	**Emergency**	94.4 (1.8)	7.73 (0.3)	9.79 (0.2)	27.98 (4.2)	88.41 (6.5)	63.2 (1.9)	58.7 (14.6)	22.2 (0.9)
	Self-init.	96.3 (3.5)	8.15 (0.1)	9.62 (0.2)	45.00 (0.0)	80.64 (2.8)	63.6 (2.0)	55.4 (8.6)	22.8 (3.3)
	Delta (%)	2.0%	5.4%	−1.7%	60.8%	−8.8%	0.6%	−5.7%	2.4%
C – Substantial	**Emergency**	69.5 (22.3)	6.72 (0.6)	9.79 (0.2)	19.29 (6.3)	79.64 (6.9)	53.8 (8.2)	67.1 (7.4)	24.7 (4.2)
	Self-init.	70.9 (26.0)	7.04 (0.6)	9.34 (0.4)	23.90 (6.2)	84.21 (6.9)	54.9 (10.2)	61.5 (28.7)	24.3 (8.9)
	Delta (%)	2.0%	4.9%	−4.5%	23.9%	5.7%	2.0%	−8.4%	−1.5%
A – Minimum	**Emergency**	7.3 (5.1)	5.24 (0.4)	7.33 (0.7)	22.23 (3.7)	37.63 (1.9)	19.2 (4.6)	56.6 (2.4)	29.4 (2.2)
	Self-init.	26.8 (5.5)	6.24 (0.5)	7.96 (0.2)	27.04 (4.8)	67.20 (5.2)	41.5 (9.0)	75.9 (3.5)	38.8 (7.0)
	Delta (%)	266.6%	18.9%	8.6%	21.6%	78.6%	116.2%	34.1%	31.8%

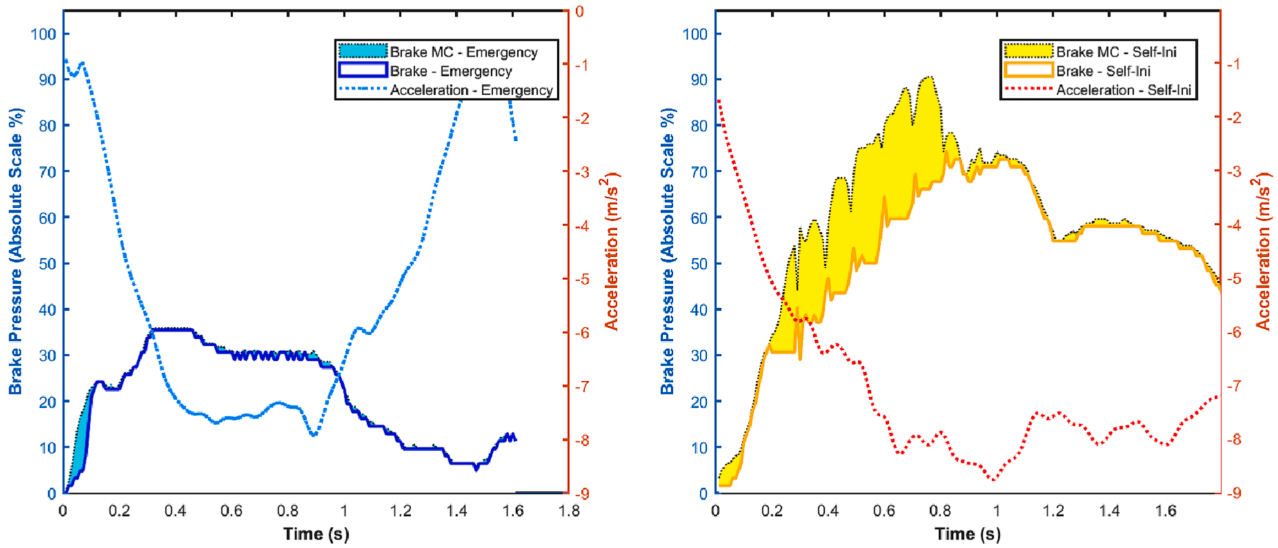

Fig. 8. Different behaviour of rider classified as A – Minimum usage of front ABS for braking in 'emergency test' (left) and 'self-initiated test' (right).

that an emergency situation in which riders have less time to plan the braking manoeuvre is different from self-initiated braking (Huertas-Leyva et al. 2019) has also been confirmed with a motorcycle with ABS for less skilled riders performing the test. The fact that the initiation of braking was not planned by the participants makes the riders' performance more realistic to be compared to a real emergency situation where the use of ABS can avoid a collision. The motorcycle of the test was particularly heavy and not easily manoeuvrable when stationary. This may have caused some riders, despite the experience and considerable time spent becoming familiar with the vehicle, to feel more insecure when braking than they would have on a smaller motorcycle. In our sample, the least skilful rider based on the braking tests was precisely the motorcyclists with the shortest height (170 cm). In any case, the difficulty in applying the brake lever while counteracting the large inertial forces during emergency braking may be a common constraint for people of low muscle mass and short height who ride smaller motorcycles/scooters that should always be considered. This work, focuses on experienced riders, identified rider profiles covering a complete range of ABS usage. Test inclusion of (i) less skilled riders (who are more likely to lose control on the road); (ii) young riders; (iii) female riders, and (iv) different road conditions (e.g. wet asphalt) could affect the generalisability of the study results in terms of the actual ratio of riders representing the identified profiles. Further research is recommended with a larger test sample considering diversity in experience level, age, and gender of the participants to determine what is the actual proportion of riders who lack the required braking skills to activate ABS during most of the braking time.

ABS is demonstrated to reduce stopping distances and to improve stability under all braking conditions, but our study shows that such features are not enough to guarantee a good braking performance in emergency events if the riders have not the skills to use the full braking power of the motorcycle. Less skilled riders, even with ABS, may not have the confidence to increase braking power further when reaching high decelerations that push them to the limit of their stabilisation control in emergency braking, thus increasing braking distance with potentially life-threatening consequences. Our results suggest that many experience riders still need knowledge and skill to make the ABS work to its optimum in emergency events to avoid crashes. The results also endorse the emergency test used in this research because in addition to the increased workload represented by the need to scan for hazards, riders responded more closely to a real emergency situation. Furthermore, the scenario design, through training, may support the generation of automatisms that help motorcycle riders to react more safely by coupling the perception-braking action task in an emergency scenario.

Practical implications of the study results may have an incidence on the design of rider training programmes. Previous research with young drivers who received ABS training showed that specific training can improve braking performance (Mollenhauer et al., 1997; Petersen et al., 2006) but also warned that, without reinforcement, the learnt braking skills could disappear within a short period of time. The authors reported that some drivers were unfamiliar with certain types of brake pedal ABS feedback to understand when it was being activated. In the case of motorcycles, where both front and rear ABS can be used independently, trainers should be aware that this understanding may be even more difficult, as novice riders may not be able to distinguish between a single ABS activation (rear only) or a combined activation (rear plus front ABS), which may lead to stop increasing the force on the front brake lever during the braking action. Furthermore, programmes should emphasise the importance of reinforcing learning, e.g. by suggesting that braking in the ABS control range be practised periodically during motorcycle rides. The findings also point to an opportunity to improve the design of braking safety systems so that they are able to improve performance for less skilled riders or even for those who lack the strength to apply maximum lever pressure in a short time. Systems with the potential to adapt to each rider's maximum braking capability, such as Emergency Brake Assist (EBA) which enhances braking by applying additional brake pressure in an emergency where the rider brakes quickly but insufficiently, or combined braking systems (CBS) which apply brake pressure to both brakes even when only one brake is applied, can help to significantly reduce braking distance in cases where braking performance is insufficient.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aap.2023.107148.

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