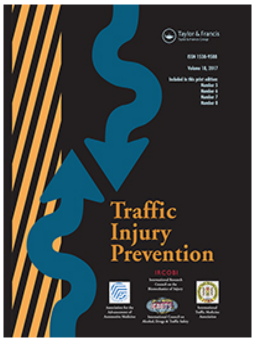

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Emergency braking is affected by the use of cruise control

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ABSTRACT

Objective: We compared the differences in the braking response to vehicle collision between an active human emergency braking (control condition) and cruise control (CC) or adaptive cruise control (ACC).

Methods: In 11 male subjects, age 22 to 67 years, we measured the active emergency braking response during manual driving using the accelerator pedal (control condition) or in condition mimicking CC or ACC. In both conditions, we measured the brake reaction time (BRT), delay to produce the peak braking force (PBD), total emergency braking response (BRT + PBD), and peak braking force (PBF). Electromyograms of leg and thigh muscles were recorded during braking. The tonic vibratory response (TVR), Hoffman reflex (HR), and M-waves were recorded in leg muscles to explore the change in sensorimotor control.

Results: No difference in PBF, TVR amplitude, HR latency, and H_{max}/M_{max} ratio were found between the control and CC/ACC conditions. On the other hand, BRT and PBD were significantly lengthened in the CC/ACC condition (240 ± 13 ms and 704 ± 70 ms, respectively) compared to control (183 ± 7 ms and 568 ± 36 ms, respectively). BRT increased with the age of participants and the driving experience shortened PBD and increased PBF.

Conclusions: In male subjects, driving in a CC/ACC condition significantly delays the active emergency braking response to vehicle collision. This could result from higher amplitude of leg motion in the CC/ACC condition and/or by the age-related changes in motor control. Car and truck drivers must take account of the significant increase in the braking distance in a CC/ACC condition.

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Emergency braking; cruise control; adaptive cruise control; biomechanics; sensorimotor control

Introduction

The braking reaction behavior to an oncoming car collision, including the measurement of braking reaction time (BRT) and muscle activation of the lower extremity muscles at the collision moment, has been well documented during manual driving using the accelerator pedal, the control condition in this study (Behr et al. 2010; Bélanger et al. 2015; Engström et al. 2010; Gao et al. 2015; Loeb et al. 2015; Montgomery et al. 2014). Some of these studies (Bélanger et al. 2015; Loeb et al. 2015; Montgomery et al. 2014) clearly showed age and gender differences in response to collision, where the time to collision at brake application was significantly higher among females (Montgomery et al. 2014) and older subjects (Bélanger et al. 2015). In addition, Loeb et al. (2015) showed strong differences between experienced and novice drivers in the brake pressure applied.

On the other hand, we found few quantitative data in the literature on the braking response to collision when using a cruise controller (CC) that controls the speed of a motor vehicle. This condition is also present when using an adaptive cruise controller (ACC) that automatically adjusts the vehicle speed to maintain a safe distance from vehicles ahead. In these 2 driving conditions, the right foot stays on the floor of the vehicle and thus is not in close proximity to the brake pedal. When an emergency braking response is needed in a CC/ACC condition one could suppose that the amplitude of the leg displacement should increase, which may delay the brake reaction time. Some studies have examined brake reaction times in CC/ACC conditions. Lee et al. (2007) examined the sensitivity of the driver to brake pulses of different amplitudes and durations in situations that exceed the capability of ACC, but their data were not compared to those obtained during manual driving in the absence of any ACC. In their review of the literature, Young and Stanton (2007) reported empirical data to determine how brake reaction times could be affected by vehicle automation. Compared to data gathered during manual driving, the authors report a striking increase in reaction times for automated driving conditions. Some studies report that ACC results in improved awareness compared to manual driving, with ACC drivers attending more to the roadway (de Winter et al. 2014; Stanton and Young 2005). However, others (Vollrath et al. 2011) have shown that delayed driver reactions occurred in critical situations when driving with CC or ACC. Thus, any possible alteration in brake reaction time in CC/ACC conditions could result from multiple factors including reduced awareness and/or altered biomechanical and physiological factors.

When using the accelerator pedal during emergency braking, the relative parts of electromyographic activation of thigh and leg muscles have been determined (Behr et al. 2010) but never in the CC or ACC condition.

Our primary objective was to test the hypothesis that the CC/ACC condition could lengthen the emergency braking

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response to vehicle collision and thus the braking distance. This hypothetical lengthening of the braking duration could simply result from the increased amplitude of leg motion to reach the brake pedal when using the speed controller. This condition of cruise control could also alter the reactivity of the driver to an oncoming collision. Indeed, we already showed that driving a car at a high speed for a prolonged period modified the sensorimotor control of leg muscles controlling the foot position on the accelerator pedal (Jammes et al. 2016). The occurrence of such an altered sensorimotor control in leg and foot muscles during driving with the speed controller may be questionable.

Methods

Ethical approval

This research adheres to the principles of the latest revision of the Declaration of Helsinki. The protocol was submitted to and approved by our institutional committee (CPP Sud Mediterranée 1). The procedures were carried out with the adequate understanding and written consent of the subjects.

Participants

Eleven healthy male subjects (mean age: 42 ± 5 years; age range: 22 to 67 years; mean weight: 83 ± 5 kg) were explored. All were free of foot pain and had no history of trauma or surgery on their feet and legs. None were involved in an exercise program. Their driving experience varied between 2 and 50 years. We examined only male participants because there our institution is majority male. In addition, because Montgomery et al. (2014) showed marked gender differences in emergency braking reactions, the inclusion of females would oblige us to study a large number of subjects.

Instrumentation

As detailed in our previous study (Jammes et al. 2016), a homemade apparatus was built using auto parts, including a driver's seat, wheel, steering column, and brake and accelerator pedals. A standard emergency braking configuration has been already proposed by our team (Behr et al. 2010). Adjusting both the car seat height and position allowed fixing the initial joint flexion angles to 96°, 56°, and 13° for the right hip, knee, and ankle, respectively.

To measure the braking force, a compression load cell was fixed under the brake pedal (Scaime model K22, AS Technologies, Langlade, France; linear from 0 to 2,000 N). The articulated support of the accelerator pedal was also connected to a push–pull rod load cell (Scaime model ZF 100, AS Technologies; linear from 0 to 1,000 N). Electric contacts were fixed on the (1) accelerator pedal, (2) brake pedal, and (3) vehicle floor in front of the accelerator pedal. The 3 signal outputs were fed to a numerical oscilloscope (Gould model DSO 400, Ballainvilliers, France). The output signal from the load cell measuring the braking force was also fed to this oscilloscope.

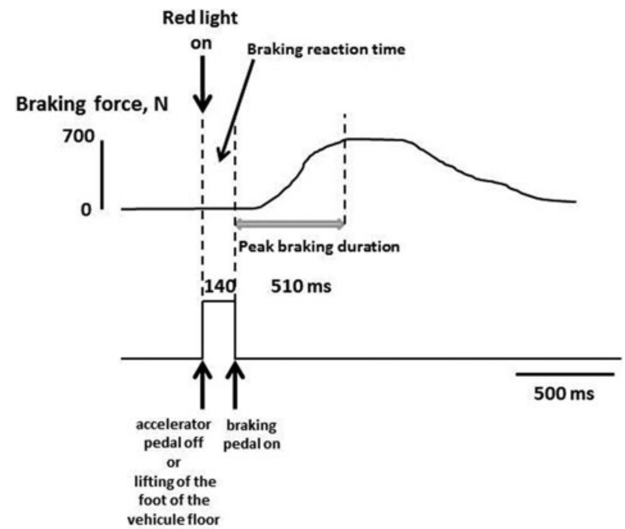

Figure 1. Example of recordings of time and mechanical events during emergency braking. Measurements of BRT (the time to displace the foot from the accelerator to the brake pedal), PBD (the time to reach PBF), and PBF.

Measurements

Braking pattern

Cursors on the oscilloscope screen allowed accurate calculation in each condition (control or CC/ACC): (1) BRT—that is, the time to displace the foot from the accelerator or the floor to the brake pedal; (2) the peak braking duration (PBD)—that is, the time to reach the peak braking force; and (3) the peak braking force (PBF). Figure 1 shows an example of measurements of duration and amplitude of the mechanical events during emergency braking.

Prior to each experiment, the subject was instructed to maximally push on the brake pedal to full pedal displacement to measure the maximal plantar flexion force (F_{max}). Three consecutive maneuvers were performed, and F_{max} corresponded to the maximal force value. During these maneuvers, electromyographic (EMG) activities were recorded in thigh and leg muscles and quantified by root mean square (RMS), and the maximal RMS values were measured.

EMG recordings and analyses

Bipolar (30 mm center-to-center) Ag-AgCl surface electrodes (model 13L20, Dantec Medtronic, Skovlund, Denmark) were used to measure in the right leg EMG voltage from the tibialis anterior (TA), gastrocnemius medialis (GM), rectus femoris (RF), and biceps femoris (BF) muscles. EMG signals were measured (Dantec Disa Medtronic, Diagramma AG, Dietikon, Switzerland) and amplified (gain = 5,000), with the frequency band ranging from 10 to 10,000 Hz. The software program allowed calculating the power spectrum and the EMG signal was digitized with a sampling frequency of 2,000 Hz using the data acquisition card mounted in the computer. For each contraction, an averaged power spectrum was obtained from 6 128-ms window epochs overlapping each over by half their length for a total segment of 512 ms. The software program calculated the RMS, an index of global EMG energy. Raw and RMS EMG values were simultaneously recorded on a polygraph (TA

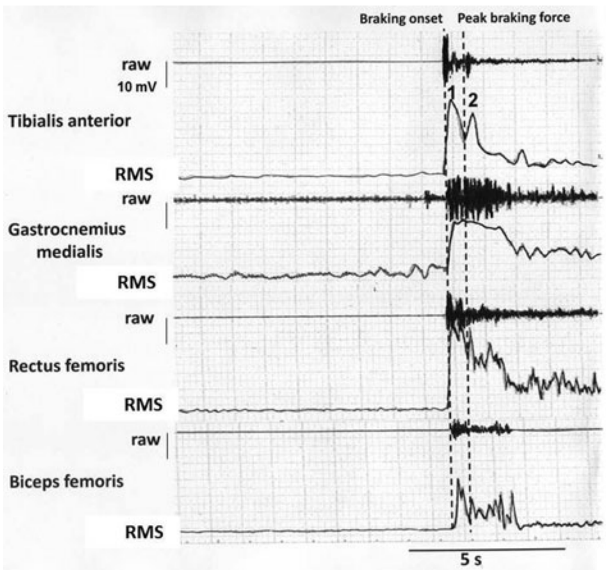

Figure 2. Successive EMG components recorded in leg and thigh muscles during one braking session. Raw EMG activities and their quantification using RMS transformation are shown. A short activation phase introduced the (1) braking onset, preceding the production of the (2) peak braking force. Only units of raw EMG activities were performed. RMS values are in arbitrary units.

400 Gould, Ballainvilliers, France) during all braking maneuvers. For each braking action we measured the first peak RMS value during the short activation phase and then the muscle activation needed to produce the peak braking force. Figure 2 shows the successive EMG components during one braking session.

TVR recording

Measurement of the tonic vibratory response (TVR) provides an indication of the magnitude of the myotatic reflex, which adjusts the motor command to the changes in muscle length. TVR includes the mechanical activation of muscle spindles, the reflex control of gamma and alpha spinal motoneurons, the nerve conduction in both afferent and efferent fibers, and the motor command by the alpha and gamma motoneurons (Ghez 1985). The central nervous system modulates the myotatic reflex through its action on the gamma motoneurons. Thus, the behavior is known to influence the TVR magnitude (Prochazka et al. 2002). As in our previous driving study (Jammes et al. 2016), mechanical vibrations were delivered by an electromagnetic vibration generator (Vibralgic 4, Electronic Conseils, Ales, France). The optimal TVR amplitude was measured for a vibration frequency of 80 Hz. The TVR magnitude was computed by integration of raw EMG signals from TA and GM muscles and plateaued before the end of a 3-s period of vibration. The 3-s vibration periods were separated by 10-s epochs.

M-wave and H-reflex

To simultaneously record the muscle action potential (M-wave) and the Hoffman reflex (H-reflex) in the GM muscle, we followed the recommendations of Palmieri et al. (2004), which were reproduced in our previous study (Jammes et al. 2016). The cathode was placed over the common peroneal nerve to the lateral aspect of the leg around the head of fibula, and the anode was placed superior to the patella. Two skin electrodes were used to ensure that the stimulating sites to elicit the M-wave and H-reflex during the control and CC/ACC conditions were exactly the same. A neurostimulator (Grass S88, Quincy, MA) delivered 1.0-ms rectangular pulses every 10 s through an isolation unit. The M- and H-waves were fed to an oscilloscope (Gould model DSO 400, Ballainvilliers, France), permitting an average of 16 successive potentials to calculate peak-to-peak amplitude and latency. The maximal H-reflex amplitude was standardized to the maximal M-wave amplitude. Only the H_{max}/M_{max} ratio was considered.

TVR, H-reflex components, and M-waves were recorded before the braking sessions when the foot was placed on the accelerator pedal (control condition) or the vehicle floor (CC/ACC condition).

Experimental procedure

The subject was instructed to maximally brake when a red flashlight illuminated in nondriving sessions and also at the end of each driving session. First, to train the subject for emergency braking, he drove for short periods (1 min) in the CC/ACC condition, with the right foot staying of the car floor (5 events), or in the control condition, with the right foot pushing on the accelerator pedal (5 events). In each one, the subject had to brake at the end of each session. The 2 conditions were completed in random order. Second, the subject was instructed to alternatively drive for 5-min periods either using the speed controller or not and to brake at the end of each session. EMGs, TVR, M-wave, and H-reflex were recorded during each 5-min driving sessions. Five control sessions and 5 sessions in CC/ACC condition were performed. During driving in the control condition, the subject was asked to maintain a constant force on the pedal at 20 N, a force value corresponding to approximately 120 km.h^{-1} (data provide for a Volkswagen Golf car by IDIADA Automotive Technology SA, Tarragona, Spain). Figure 3 shows a schematic drawing of the protocol.

Thus, a total of 20 braking tests were considered for each individual (10 with the speed controller and 10 with the accelerator pedal).

To verify that the force applied for 5 min on the accelerator pedal did not influence the braking characteristics, in 1 of 3 subjects the braking pattern was also measured in 20 driving sessions during which the subject had to alternatively drive for 5 min while maintaining a force of 10 N (near 60 km.h^{-1}, 10 sessions) or 20 N (120 km.h^{-1}, 10 sessions) on the accelerator pedal. Data were also compared to those measured when using the speed controller for the same participants.

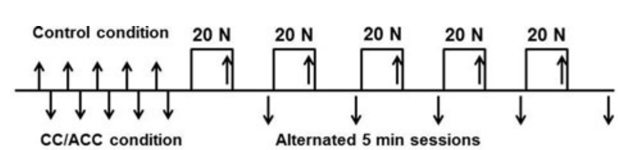

Figure 3. Schematic drawing of the protocol. The study began with 10 emergency braking epochs during which the subject was asked to successively drive under either the CC/ACC condition (downward arrows) or with the right foot pushing on the accelerator pedal in the control condition of manual driving (upward arrows). This was followed by 5 sessions where the subject had to alternatively drive for 5 min in the CC/ACC condition or not and to brake at the end of each session. Arrows indicate the instants of emergency braking (upward arrows: end of each manual driving session; downward arrows: end of each CC/ACC session).

Table 1. Braking components during driving conditions mimicking that of CC or ACC or pushing on the accelerator pedal to drive (control). Peak RMS values of EMGs are measured at the premotor phase and then during production of the peak braking force.[a]

	Control	CC/AC
Braking reaction time (ms)	183 ± 7***	240 ± 13
Peak braking duration (ms)	568 ± 36*	704 ± 70
Emergency braking response (ms)	750 + 34**	913 + 47
Difference in braking response (ms)	164 + 34	
Peak braking force (N)	759 ± 74	820 ± 80
Peak braking force (% F_{max})	68 ± 3	72 ± 4
RMS TA premotor (% RMS max)	38 ± 3 (94 ± 4)	40 ± 2 (106 ± 8)
RMS TA braking (% RMS max)	17 ± 2 (46 ± 5)	20 ± 2 (54 ± 6)
RMS GM premotor (% RMS max)	41 ± 2 (102 ± 4)	42 ± 3 (101 ± 3)
RMS GM braking (% RMS max)	24 ± 2 (60 ± 5)**	36 ± 3 (90 ± 4)
RMS RF premotor (% RMS max)	35 ± 4 (97 ± 5)	39 ± 4 (108 ± 6)
RMS RF braking (% RMS max)	13 ± 3 (36 ± 5)	18 ± 5 (50 ± 4)
RMS BF premotor (% RMS max)	41 ± 5 (87 ± 4)	42 ± 5 (89 ± 5)
RMS BF braking (% RMS max)	12 ± 2 (26 ± 5)	11 ± 2 (23 ± 6)

[a]RMS values in parentheses are expressed as a percentage of values measured during production of the maximal plantar flexion force. Values are mean ± SEM of 110 measurements performed in each condition for all 11 subjects (control and CC/ACC). Asterisks denote significant changes between the 2 conditions, *$P < .05$; **$P < 0.01$; ***$P < .001$.

Data analyses and statistics

Data are presented as mean ± standard error of mean (SEM). The statistical software (Sigmaplot 11.0, Jandel, Germany) allowed the use of analysis of variance for repeated measures when the variables were normally distributed and Friedman's test for repeated measures when they were not. We searched for differences between the braking characteristics, EMG amplitudes, TVR, M-wave, and H-reflex between the 2 situations (control and CC/ACC). During the braking actions, the EMG amplitude was related to its peak value measured at the beginning of experience when measuring the peak braking force. Least squares regression analyses were used to study the effect of age or driving experience on the braking characteristics. Student's *t* test compared the slopes of regression lines with their SEM. Significance for analysis of variance, Friedman's test, and Student's *t* test was accepted if $P < .05$.

Results

Peak braking force and peak RMS values of EMGs

The mean PBF was 1,071 ± 63 N. Peak RMS values were measured when producing PBF. For the TA, GM, RF, and BF muscles, the RMS values (expressed in millivolts) were 37 ± 2, 40 ± 2, 36 ± 3, and 47 ± 6, respectively.

Braking patterns

Table 1 shows the mean values of the different components of braking patterns during braking actions in the control and CC/ACC conditions. Only the BRT, PBD, and total emergency braking response (BRT + PBD) significantly differed between the 2 conditions. The CC/ACC markedly lengthened both BRT and PBD but did not affect the peak braking force. The integrated EMG values measured during braking action were significantly higher in the GM muscle in the CC/ACC condition.

Table 2. Measurements of TVR in the TA and GM muscles, the H-reflex, and the M-wave in the GM muscle during driving conditions mimicking that of cruise control (CC/ACC condition) or pushing on the accelerator pedal (control). The ratio between the maximal amplitudes of the H- and M-waves was computed. No significant differences were noted between the 2 conditions.

		Control	CC/ACC
TVR	TA	26 ± 4	29 ± 3
TVR	GM	28 ± 3	28 ± 3
H-reflex latency (ms)		40 ± 3	38 ± 3
Ratio H_{max}/M_{max} (%)		48 ± 5	44 ± 5

Spinal reflexes

Table 2 indicates that the TVR amplitude in TA and GM muscles did not significantly vary between the 2 experimental conditions. In addition, the H-reflex latency and the H_{max}/M_{max} ratio in the GM muscle were constant.

Driving at different speeds

Exerting a 10 or 20 N force on the accelerator pedal in the control condition did not significantly affect BRT and PBD values. When producing a 10 N force, BRT and PBD were respectively 202 ± 11 and 554 ± 55 ms, compared to 189 ± 11 and 568 ± 40 ms with the 20 N force. In addition, PBF did not vary.

Effects of the age and driving experience on the braking pattern

Age-related changes in BRT were found (Figure 4). In both conditions, the braking response to collision was lengthened among older participants and the slope of regression line between BRT and age was significantly higher ($P < .05$) in the CC/ACC condition (Figure 4A). The difference between BRT values measured in both conditions (delta BRT) also increased with age (Figure 4B). On the other hand, PBD decreased with driving experience (and age) in both experimental conditions (Figure 5A), which also reduced the difference between PBD values measured in both conditions (Figure 5B). This resulted in the absence of any age dependence of the total duration of the response to emergency braking (sum of BRT and PBD values). Driving experience also enhanced the peak braking force but only in the control condition (Figure 6).

Discussion

The main observation of the present study was that the CC/ACC condition significantly and markedly lengthened the reaction time during emergency braking (BRT) as well as the time between the contact on the brake pedal and the production of the peak braking force (called the peak braking duration or PBD). The mean total lengthening of braking latencies (sum of BRT and PBD values) measured in the CC/ACC condition was 164 ± 34 ms and corresponded to a substantial increase in the braking distance (5.5 m) compared to those measured when driving at 120 km.h^{-1} during manual driving (control). The increase in braking distance was reduced (2.7 m) but remained substantial when driving at 60 km.h^{-1}. The existence of an enhanced amplitude of the leg motion during emergency braking in the CC/ACC condition was supported by higher EMG

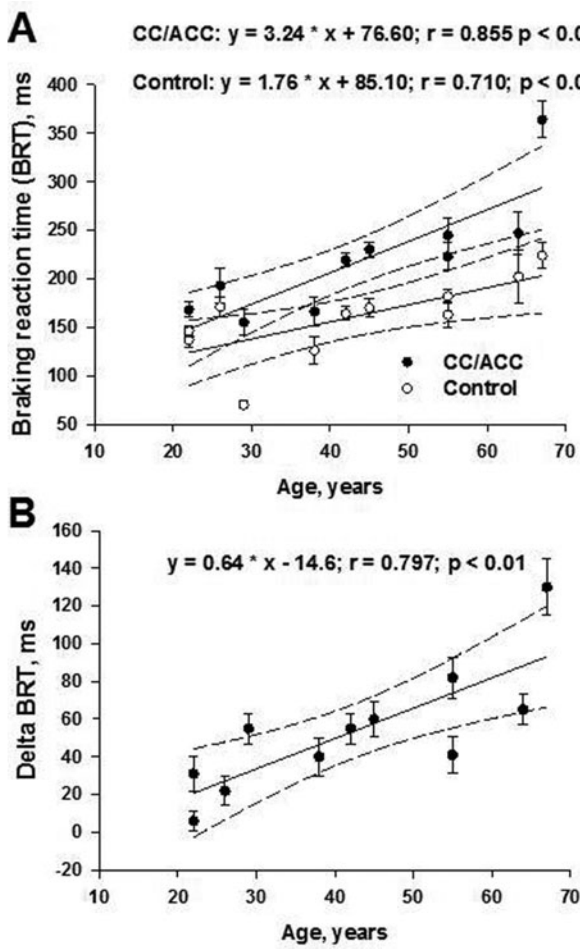

Figure 4. Regression analysis with 95% confidence intervals between BRT and age for all 11 subjects. (A) Compared to the control condition of using the accelerator pedal, the slope of the regression line was significantly ($P < .05$) higher in the CC/ACC condition. (B) The difference between BRT values measured in both conditions for each individual also increased with age.

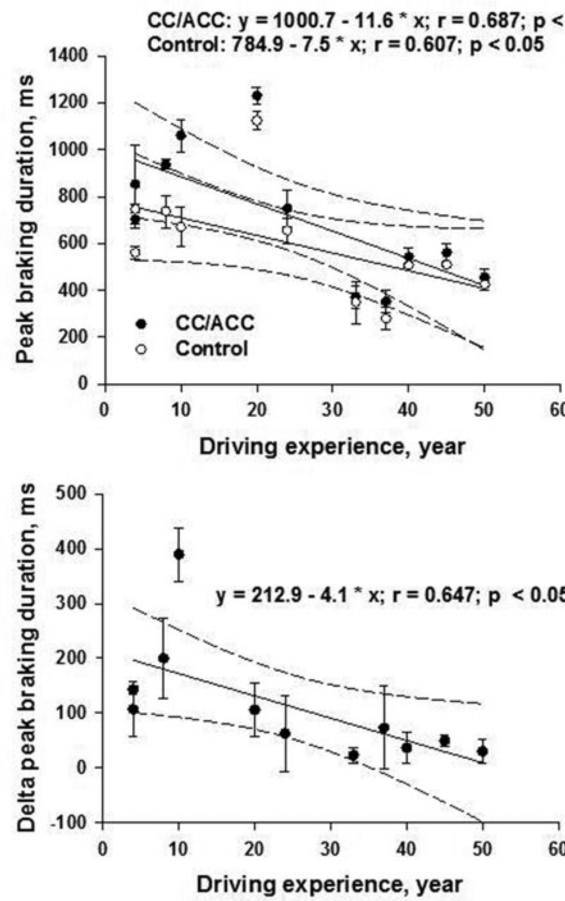

Figure 5. Regression analysis with 95% confidence intervals between PBD and driving experience for all 11 subjects. (A) The slopes of the regression lines did not significantly differ between the control and CC/ACC conditions. (B) The difference between PBD values measured in both conditions fir each individual decreased with driving experience.

recruitment in the GM muscle in this situation. The age of the participants significantly lengthened BRT values, and the effect was accentuated in the CC/ACC condition. On the other hand, driving experience reduced PBD in both driving conditions and facilitated the production of the peak braking force; however, this was only observed in the control condition.

We cannot compare our data to the literature data on biomechanical and EMG events occurring in emergency braking in the CC/ACC condition. As mentioned previously, the literature is mostly based on empirical data to determine how brake reaction times could be affected by vehicle automation (Vollrath et al. 2011; Young and Stanton 2007). These studies indicated increased reaction times in critical situations when driving with CC or ACC.

The main limitation of the present study was the absence of data for females. Indeed, the study by Montgomery et al. (2014) showed differences in BRT by gender in response to collision. Thus, the present data on the differences between braking reaction times in the control and CC/ACC conditions cannot be extrapolated to females.

Our data confirm that driving experience significantly increases the brake pressure (Loeb et al. 2015), but this was only verified in the control condition. We also corroborated the observations by Bélanger et al. (2015) that the time to collision at brake application was lengthened among older subjects during manual driving (control condition) and we showed that this limitation was accentuated in the CC/ACC condition.

Our data on EMG quantification during emergency braking actions corroborate data obtained in situations of manual driving (Behr et al. 2010). Indeed, the RMS values measured in the thigh muscles, expressed as a percentage of the maximum activation level, were in the same range as in Behr et al.'s (2010) study.

We found no difference in the myotatic and H-reflex measured in leg muscles in both driving conditions. This contrasts with our previous data where we reported a significant reduction in the myotatic reflex in the TA muscle when driving for 60 min in the control condition (Jammes et al. 2016). In the present protocol, the absence of an altered reflex control in leg muscles during 5-min periods of driving could accentuate the difference in braking reaction times measured in both conditions. Indeed, it may be hypothesized that the altered reflex control of leg muscles during the 60-min driving period in the control condition could delay braking reaction time, reducing the difference between emergency responses. In fact, we already showed that the brake reaction time was not delayed after the 60-min driving trials in the control condition (Jammes et al. 2016).

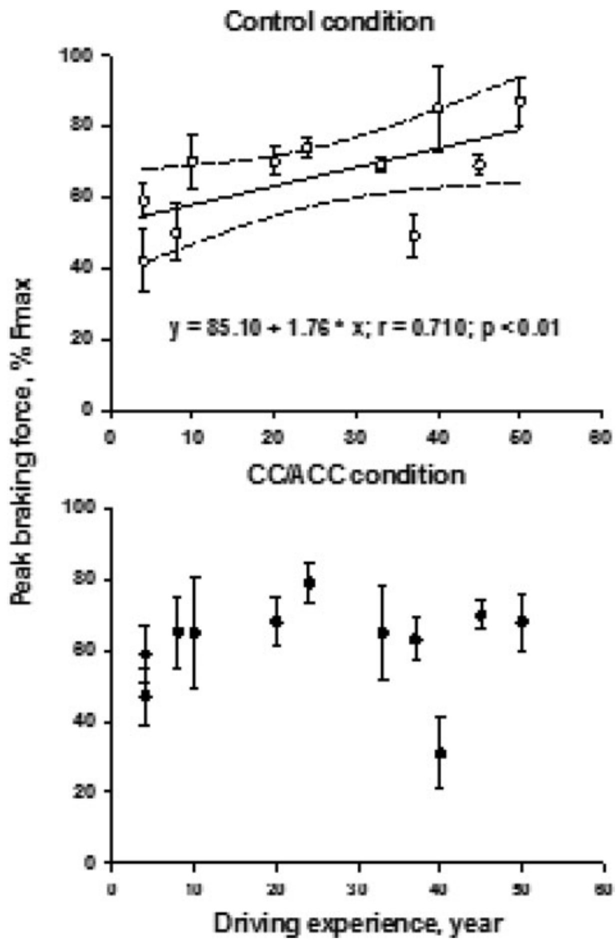

Figure 6. Driving experience significantly increased the braking force only in the control condition.

In conclusion, the most striking difference measured between the control and the CC/ACC conditions is the delayed reaction time during emergency braking when male subjects used a speed controller. Car and truck drivers should take into account the significant increase in braking distance when using a speed controller. Car manufacturers should propose ergonomic solutions to reduce the amplitude of leg motion needed to reach the brake pedal. Indeed, the enlarged amplitude of leg motion seems to be the major cause of the delayed reaction time.

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