Simulator study of young driver’s instinctive response of lower extremity to a collision

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Objective: A driver’s instinctive response of the lower extremity in braking movement consists of two parts, including reaction time and braking reaction behavior. It is critical to consider these two components when conducting studies concerning driver’s brake movement intention and injury analysis. The purposes of this study were to investigate the driver reaction time to an oncoming collision and muscle activation of lower extremity muscles at the collision moment. The ultimate goal is to provide data that aid in both the optimization of intervention time of an active safety system and the improvement of precise protection performance of a passive safety system.

Method: A simulated collision scene was constructed in a driving simulator, and 40 young volunteers (20 male and 20 female) were recruited for tests. Vehicle control parameters and electromyography characteristics of eight muscles of the lower extremity were recorded. The driver reaction time was divided into pre-motor time (PMT) and muscle activation time (MAT). Muscle activation level ($A_{COL}$) at the collision moment was calculated and analysed.

Results: PMT was shortest for the tibialis anterior (TA) muscle (243–317 ms for male and 278–438 ms for female). Average MAT of the TA ranged from 28-55 ms. $A_{COL}$ was large ($5-31\%$ for male and $5-23\%$ for female) at 50 km/h, but small ($<12\%$) at 100 km/h. $A_{COL}$ of the gluteus maximus was smallest ($<3\%$) in the 25 and 100 km/h tests. $A_{COL}$ of RF of men was significantly smaller than that of women at different speeds.

Conclusions: Ankle dorsiflexion is firstly activated at the beginning of the emergency brake motion. Males showed stronger reaction ability than females, as suggested by male’s shorter PMT. The detection of driver’s brake intention is upwards of 55ms sooner after introducing the electromyography. Muscle activation of the lower extremity is an important factor for 50 km/h collision injury analysis. For higher speed collisions, this might not be a major factor. The activations of certain muscles may be ignored for crash injury analysis at certain speeds, such as gluteus maximus at 25 or 100 km/h. Furthermore, the activation of certain muscles should be differentiated between males and females during injury analysis.

Introduction

Vehicle safety is affected by drivers, vehicles, and road conditions. The instinctive response that a driver has when facing an oncoming collision is key for studies about active vehicle safety systems considering the driver's brake movement intention and intervention time, and passive vehicle safety systems consider the occupant seating posture and musculoskeletal characteristics (Bose et al. 2010; Lie et al. 2010; Yu 2009).

A driver’s instinctive response consists of 2 parts, reaction time and braking reaction behavior. Reaction time, which represents the reaction ability when facing emergencies, is defined as the time between the emergency onset and the release of accelerator. It is important when considering traffic accident reconstruction, brake intention detection, and the active vehicle safety system design (Jurecki and Stańczyk 2009; Lie et al. 2004). Studies regarding driver reaction time are traditionally based on the classical theory of automobiles, in which the control parameters are the accelerator and the brake pedal (Liebermann et al. 1995; Yu 2009). Reaction time was considered to be the start of brake intention and was broadly used as the intervention time of active safety systems, such as the braking assistant system, which effectively slows the vehicle once the intention is detected. However, this system cannot fully satisfy safety needs, which require earlier detection of braking intention.

It is well known that a change in electromyography (EMG) signal occurs prior to movement, and this has been commonly used in psychology and kinesiology (Sandoval 2010; Weiss 1965). EMG changes significantly during movement of the lower extremities, which occurs between the discovery of an emergency and the increase of braking force. Therefore, EMG is used to divide reaction time into pre-motor time (from the stimulus onset to the EMG change) and motor time (from EMG change to the time of movement). Motor time is defined as the time saved by EMG so that early detection can be achieved. A braking
assistant system can be activated earlier and the braking distance shortened, so the drivers are better protected. However, EMG has rarely been introduced into studies about driver reaction time, so more works should be performed (D’Addario et al. 2014; Seto et al. 2004).

Braking reaction behavior is the instinctive posture when facing emergencies, including the leg’s motion when moving from the accelerator to the brake and its muscle tensing and bracing when feeling panic. The electromyography characteristic, such as muscle activation level, is a major parameter representing the instinctive posture. This characteristic tends to alter the kinetic and kinematic behaviors during a crash (Rudd et al. 1998). Beeman et al. (2012) showed that bracing and muscle activation decreased the occupant’s kinematic response. Hardin et al. (2004) compared lower extremity injuries in different muscle conditions (no activation, minimum activation, and maximum activation) and found that increasing muscle activation resulted in a higher force on the ankle joint and Achilles tendon, which exacerbates axial loading injuries.

EMGs with large differences were utilized for qualitative analysis, and the results showed that muscle activation affects occupant injury during collision (Hardin et al. 2004). However, muscle activation takes time; muscles are not always in minimum or maximum activation states when an emergency occurs. A passive safety system based on qualitative injury analysis might not protect the occupant precisely, because it cannot fully describe the actual muscle state at the exact moment of collision. Hence, it is important to study these precise electromyography characteristics to improve the performance of the passive safety system (i.e., airbag).

A driver’s instinctive response is affected by gender, age, and cognitive ability (Leung et al. 2012; Martin et al. 2005; Philip et al. 2005; Warshawsky-Livne and Shinar 2002; Young and Stanton 2007). Among them, gender is considered as an important factor, due to the innate difference between genders and the growing number of female drivers. Research conducted by Jurecki et al. (2014) showed that the braking reaction time varied...
Figure 3. Premotor time (PMT) in the simulated collision tests for (A) males and (B) females. Significant difference exists between different driving speeds (∗), different muscles (#), and different genders (†).

Figure 4. Muscle activation time (MAT) for (A) males and (B) females. MAT is significantly larger (∗) or smaller (#) than zero. Significant difference exists between different genders (†).

with speed at the emergency moment, so driving speed should also be a focus. Thus, the influence of speed and gender on driver’s instinctive responses were studied.

This study investigated drivers’ instinctive responses to an oncoming collision while combining electromyography characteristics of the lower extremities. Considering the potential risks of field testing, a simulated collision scene with an obstacle car cutting suddenly into the host lane was constructed in a driving simulator, and the instinctive responses of 40 drivers were tested. The vehicle control parameters and EMG of 8 major muscles of the lower extremities were recorded simultaneously. The reaction time of the drivers’ braking behavior and the electromyography characteristics of the lower extremities at the moment of collision were analyzed.

Methods

Participants

Forty healthy young adult (20 male and 20 female) volunteers between the ages of 23 and 28 were recruited. All participants held a valid driver’s license with several years of driving experience. The demographics of volunteers are displayed in Table A1 (see online supplement). Each participant was made aware of the simulated collision test procedure and signed an informed consent form before the test. The study was approved by the first hospital of the Jilin University Ethics Committee.

Major muscles of lower extremity

Eight major muscles related to lower extremity movement were chosen and their muscular purposes are as follows: (1) tibialis anterior (TA, ankle dorsiflexion); (2) soleus (SOL, ankle plantar flexion); (3) gastrocnemius (GAS, ankle plantar flexion and knee flexion); (4) vastus medialis (VM, knee extension); (5) vastus lateralis (VL, knee extension); (6) rectus femoris (RF, knee extension and hip flexion); (7) hamstrings (HAM, knee flexion and hip extension); (8) gluteus maximus (GM, hip extension).

Test design and procedure

For ethical reasons, simulated collision with high potential risks cannot be performed in a field test environment. Hence, a simulated collision scene was constructed in a driving simulator at the State Key Laboratory of Automotive Simulation and Control, Jilin University, China. The driving simulator was mounted on a Stewart platform, in which the yaw, pitch, and roll motions could
The simulator was used to simulate the driver–vehicle–road environment, and data were synchronously collected from the accelerator, brake pedal, and steering wheel. The simulator was equipped with a realistic operation system, such as a force feedback steering wheel and a brake with power assist feel. The host car was surrounded by a circular screen providing the driving environment and a stereo sound system mimicking the driving noise.

According to the Annual Report of Road Accident in China (2013, provided by the Traffic Management Bureau of the Public Security Ministry), 2-lane, 2-way roads comprise 95.1% of the total roads. Driving in the opposite lane and overtaking illegally are the main causes of accidents, and frontal collisions are common. Based on the scenario used by McGehee and Carsten (2010), a scenario with a 5-km-long 2-way rural highway was constructed. The host car was driven in one lane at a designated speed. Opposing-lane traffic consisted of many vehicles with a 5 m distance between, which was crowded enough to eliminate the driver’s perception of the obstacle car. To avoid misjudgment, only the host car was in the host lane. Only one obstacle car cut into the host lane at the moment the distance between the host and obstacle cars reached a certain value.

The driving simulator and the simulated collision scene are presented in Figure 1. At $T_1$, the host and obstacle car started together. At $T_2$, the obstacle car was cutting into the host lane. At $T_3$, the obstacle car fully cut into the host lane, which occurred at a distance of 20 m.

Each participant underwent the simulation once at each of 4 different speeds, 25, 50, 75, and 100 km/h. Performing the test once at each speed reduced the learning effect as much as possible (Young and Stanton 2007). The obstacle car that cut into the host lane was random. Before the test, participants practiced in the driving simulator for 1 h in a standard scenario to become familiar with the simulator and to acquire a comfortable sitting posture. Verbal notices by the supervisor occurred when the velocity was 5 km/h higher or lower than the designated one. Therefore, muscle activations due to frequent postural change resulting from comfort and velocity adjustment were diminished. Participants were instructed to brake immediately once the obstacle car fully cut in. As a pilot study that focused on the influence of vehicle speed and gender on instinctive response, other factors were limited. All drivers were young and no fatigue was involved.

When using EMG to estimate the level of muscle activity, it is necessary to normalize the muscle activation level to the percentage of maximum voluntary contraction (MVC) based on the root mean square (RMS) value. The procedures of MVC tests were performed based on former studies (Hislop and Montgomery 2002; Kendall et al. 2005) and they are shown in the Appendices (MVC Test; see online supplement). After the MVC tests, a 1-h rest was provided before the driving behavior test.

**Data collection and processing**

The vehicle control parameters of the host car and the EMG of the lower extremities were collected during each drive. The vehicle parameters were recorded by the driving simulator, including host car speed, $V_0$ (km/h); accelerator aperture (%); and distance between the host and obstacle cars (m). The brake pedal force, $F$ (N), was recorded by a load cell transducer (EVT-14W, Shanghai Yu Ran Sensor Technology Co., Ltd.) on the brake pedal.

Surface EMG of the driver’s right leg was recorded by an MP150 physiology recorder from BioPac Systems, Inc. (CA) and 40-mm-diameter Ag/AgCl disc electrodes. Two electrodes 20 mm apart and were parallel to muscle fiber orientation (Hermens et al. 2000). The locations of Ag/AgCl electrodes, which were between the motor point and the distal tendon, were recommended by the Surface Electromyography for the Non-Invasive Assessment of Muscles project (http://www.seniam.org). The electrode locations of the GM were moved slightly upwards and outwards to avoid sitting pressure on electrodes sites. To reduce impedance at electrode sites, the participants’ skin was cleaned and sterilized with 70% alcohol. The sample rates of all apparatuses were 1,000 Hz, and the
data were collected synchronously. EMG data were subjected to a Chebyshev bandpass filter (10–350 Hz). Prior to calculation of the RMS value from EMG data, the data were full wave rectified and subjected to linear envelope processing through a second-order low-pass Butterworth filter with a 6-Hz cutoff frequency. 

$T_{\text{ORS}}$ was defined as the moment when the obstacle car cut fully into the host lane. The EMG onset was defined as the moment when the EMG signal reached 5% of maximum, indicating that the driver was preparing to perform a braking motion. $T_{\text{GOFF}}$ was defined as the moment when the accelerator aperture began to drop. $T_{\text{RON}}$ was defined as the moment when the brake pedal force began to increase, indicating that the right foot was on the brake pedal. $T_{\text{Fmax}}$ was defined as the moment when the brake pedal force reached maximum. $T_{\text{COL}}$ was defined as the moment when the distance between the 2 cars reached zero. The typical test data are presented in Figure 2.

The participant might notice the obstacle car before it cut fully into the host lane. To diminish this effect, the time it took for cutting fully into the lane was very short. The obstacle car appeared out of a lane containing many cars. This provided a visual block to the driver, which obscured the perception of the obstacle car when it was still in the opposing lane. Premotor time (PMT) was defined as the time difference between the EMG onset and $T_{\text{ORS}}$. Muscle activation time (MAT) was defined as the time difference between $T_{\text{GOFF}}$ and the EMG onset. The muscle activation level ($A_{\text{COL}}$) was defined as the ratio of RMS value at the moment of collision to that in the MVC test.

### Data statistics and analysis

PMT and $A_{\text{COL}}$ were subjected to the Kolmogorov-Smirnov test to evaluate the presence of a normal distribution. If normally distributed, they were subjected to one-way analysis of variance. If not, a nonparametric Kruskal-Wallis test was performed. $V_0$ was set as an independent variable to investigate its influence on PMT and $A_{\text{COL}}$. Variations in PMT and $A_{\text{COL}}$ between different muscles were also investigated. Post hoc pairwise comparisons using Tukey’s honestly significant difference method were performed if there were significant differences. MAT was subjected to a one-sample $t$ test with zero. PMT, MAT, and $A_{\text{COL}}$ were subjected to independent-sample $t$ tests to study the influence of gender. An alpha level of .05 was used. The mean and standard deviation were calculated for $T_{\text{COL}}$ and $T_{\text{Fmax}}$.

### Results

The results of PMT and statistical analysis are presented in Figure 3. Significant differences were found on PMT between both different $V_0$ and different muscles. MAT and the results of $t$ tests are presented in Figure 4. The average MAT of TA ranged from 28 to 55 ms, and the driver’s braking intention was first reflected by the activation of TA when facing an oncoming collision. Compared to the division method of reaction time based on vehicle control parameters only, braking intention is detected earlier when combining the EMG of the lower extremities. $A_{\text{COL}}$ at the moment of collision and the statistical results are presented in Figure 5. Of the 40 tests conducted at 25 km/h, 9 drivers (5 male and 4 female) did not collide with the obstacle car. Therefore, muscle activation in those drivers was not analyzed. Significant differences were found on $A_{\text{COL}}$ between both different $V_0$ and different muscles. Significant differences were also found between genders on PMT, MAT, and $A_{\text{COL}}$.

$T_{\text{COL}}$ and $T_{\text{Fmax}}$ are presented in Table 1. $T_{\text{COL}}$ was smaller than $T_{\text{Fmax}}$ at all speeds, indicating that the lower extremities are not fully activated at the moment of collision.

The descriptive statistics for $V_0$, PMT, MAT, and $A_{\text{COL}}$ are presented in Tables A2 to A5 (see online supplement). The normal distribution characteristics of the variables are presented in Tables A6 and A7 (see online supplement).

### Discussion

To compel the driver to generate a similar instinctive reaction as would be generated in the real world, sled tests and field tests were used. Kumar et al. (2003) and Choi et al. (2005) performed sled tests at a low velocity and measured the electromyography characteristics during collision. Behr et al. (2010) used an obstacle balloon that occurred suddenly and recorded the electromyography characteristics during emergency braking in field tests. Combining these advantages, a simulated collision scene was constructed in a driving simulator and tested at both low and high speeds. Although the realistic driving feel was slightly reduced, this method allowed for generation of a realistic enough driving experience to produce an instinctive reaction while greatly reducing the potential risk for the participants.

The reaction time was defined as the time between the stimulus onset and $T_{\text{GOFF}}$ in the traditional division method based on vehicle control parameters (Martin et al. 2010). After introducing electromyography characteristics, it was further divided into PMT and MAT in this study.

PMT was found to be smallest in the TA among the 8 major muscles for both males and females. However, significant differences were not found at every different speed or between every different muscle. Hence, the MAT of different muscles was collected and subjected to a $t$ test. MAT of TA was significantly larger than zero in all $V_0$ conditions (except for male participant 4 at 100 km/h, in which the MAT was $−3$ ms). MAT was defined as the time difference between the beginning of accelerator release and the EMG onset, which means that the muscle is activated before the accelerator is released if MAT is larger than zero. Compared to other muscles, TA was activated before the accelerator was released in most tests and had a larger MAT. In this aspect, TA is the first muscle activated when facing an oncoming collision, which agrees with Seto et al. (2004) and D’Addario et al. (2014). At 25, 50, and 100 km/h, PMTs of TAs of male drivers were significantly smaller than those of female drivers, indicating that stronger reaction ability may be presented by men.

The TA reacts the fastest when considering the combined results of PMT and MAT, indicating that the driver’s braking intention can be reflected by activation of the TA. Therefore, ankle dorsiflexion is firstly adopted when moving the lower extremities during emergency braking behavior.

Moreover, MAT can be considered as the time that is saved after introducing EMG into the detection of braking intention. The braking assistant system, which aids in deceleration, will be activated once braking intention is detected. The traditional
braking assistant system takes $T_{GOFF}$ as the start of braking intention, but it is relatively slow. The intention can be detected earlier if the EMG onset is distinguished, and the braking assistant system can be activated earlier. The average MAT of TA is 28–55 ms, which is coincident with Seto et al. (2004) and D’Addario et al. (2014). It is about 43 ms (male) at 100 km/h, indicating that the braking assistant system can start braking 43 ms earlier and the braking distance can be reduced by 1.19 m. These provide references for the optimization of intervention time in active vehicle safety systems.

A self-protection posture, including actions such as muscle tensing and body bracing, will be generated when facing an emergency. However, it takes time from the beginning of muscle activation to total activation. The collision might occur at any one of the 3 activation stages, including inactivated, becoming activated, and fully activated. The injury resulting from an accident will be influenced by the muscle activation level of the lower extremities during an accident when colliding in different stages. Therefore, muscle activation level at the moment of collision was analyzed.

For most muscles, high $A_{COL}$ was found at 50 and 75 km/h (male: 5–31%; female: 5–23%), with a maximum occurring at 50 km/h (Figure 5). This suggests that muscle activation should be considered an important value when performing injury analysis at these speeds. The lowest $A_{COL}$ occurred at 100 km/h (male: 2–9%; female: 1–12%), which can be explained by the normal driving posture at the moment of collision due to the driver’s inability to react at a high driving speed. Therefore, muscle activation level might not be a major factor in the injury analysis at 100 km/h. Differences between $A_{COL}$ between muscles and genders were significant. $A_{COL}$ of the GM were lowest (<3%) for 25 and 100 km/h tests, implying that muscle activation of the GM can be ignored for injury analysis at these speeds. For RF of all $V_0$, $A_{COL}$ for men was significantly lower than that for women, which may be due to the relatively high MVC for men. Therefore, some muscles should be differentiated between men and women during injury analysis.

Compared to prior studies, $A_{COL}$ was relatively low in this study. This resulted from differences in the recording moment. Choi et al. (2005) calculated the average muscle activation during collision. Muscle activation level was recorded at the moment of maximum braking force by Behr et al. (2010) and Chang (2009). In this study, collision occurred prior to the moment of maximum braking force (Table 1; $T_{COL} < T_{Fmax}$). This indicates that the force of the lower extremities—that is, the muscle activation level—does not reach a maximum at the moment of collision. These provide reference for crash injury analysis requiring precise musculoskeletal characteristics.

In this study, drivers’ instinctive responses of the lower extremities were analyzed in combination with electromyography characteristics. Traditional driver reaction time was further divided into PMT and MAT, and an earlier detection of braking intention was enabled. Muscle activation level at the moment of collision was also acquired, which enhances the accuracy of crash injury analysis. Limitations of the study exist; firstly, as a pilot study using the electromyography characteristics in drivers’ instinctive responses, only the influence of speed and gender were investigated. Other factors, such as road type, age, driving experience, and cognitive ability of the driver, will be considered in the future. It should be noted that a $t$ test was used even though the sample size were less than 30 (20 for each gender). Moreover, more drivers will be recruited in the future for further research. Despite these limitations, several findings were observed:

1. The TA reacts the fastest of the 8 muscles studied, which suggests that ankle dorsiflexion is firstly adopted when moving the lower extremities during an emergency braking situation. Males showed a stronger reaction ability than females, which can be concluded by their shorter PMT times (243–317 ms for males compared to 278–438 ms for females).
2. The detection of braking intention is 28–55 ms sooner after introducing EMG characteristics. At 100 km/h, the braking distance can be reduced by 1.19 m if the detection is 43 ms earlier, which reduces the probability of a collision.
3. The highest $A_{COL}$ of the lower extremity occurs at 50 km/h (5–31% for male and 5–23% for female), indicating that the muscle activation level should considered a major factor during injury analysis at 50 km/h. For collisions occurring at 100 km/h, $A_{COL}$ is small (<12%), so it may not be a major factor. $A_{COL}$ of the GM are lowest (<3%) for 25 and 100 km/h tests, indicating that muscle activation of the GM might be ignored at these speeds.
4. $A_{COL}$ of the RF for men was lower than that for women at different speeds, indicating that some muscles should be differentiated during injury analysis when considering different genders.

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**Table 1.** The moment of collision ($T_{COL}$) and the moment of maximum brake pedal force ($T_{Fmax}$).

| $V_0$ (km/h) | $T_{COL}$ (ms) | $T_{Fmax}$ (ms) | $T_{COL}$ (ms) | $T_{Fmax}$ (ms) |
|-------------|----------------|-----------------|----------------|-----------------|
| 25          | 1112 (112)     | 1295 (307)      | 1066 (110)     | 1418 (308)      |
| 50          | 628 (36)       | 1246 (318)      | 645 (39)       | 1355 (566)      |
| 75          | 425 (27)       | 1262 (374)      | 446 (127)      | 979 (557)       |
| 100         | 314 (18)       | 1467 (654)      | 313 (20)       | 1316 (666)      |

*The values were showed in the form of mean value (standard deviation)*
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