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Mathematical Model to Predict Drivers' Reaction Speeds

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Mental distractions and physical impairments can increase the risk of accidents by affecting a driver's ability to control the vehicle. In this article, we developed a linear mathematical model that can be used to quantitatively predict drivers' performance over a variety of possible driving conditions. Predictions were not limited only to conditions tested, but also included linear combinations of these tests conditions. Two groups of 12 participants were evaluated using a custom drivers' reaction speed testing device to evaluate the effect of cell phone talking, texting, and a fixed knee brace on the components of drivers' reaction speed. Cognitive reaction time was found to increase by 24% for cell phone talking and 74% for texting. The fixed knee brace increased musculoskeletal reaction time by 24%. These experimental data were used to develop a mathematical model to predict reaction speed for an untested condition, talking on a cell phone with a fixed knee brace. The model was verified by comparing the predicted reaction speed to measured experimental values from an independent test. The model predicted full braking time within 3% of the measured value. Although only a few influential conditions were evaluated, we present a general approach that can be expanded to include other types of distractions, impairments, and environmental conditions.

Keywords: neuromuscular control, reaction speed, mathematical model, cellular phone, texting

Motor vehicle accidents are the leading cause of death for United States citizens age 4 through 34 years, according to the National Highway Traffic Safety Administration (NHTSA, 2008). Mental distractions and physical impairments can further increase the risk of accidents by affecting a driver's ability to control the vehicle. Recent studies have investigated the effect of cell phone usage (Cooper & Strayer, 2008; Horrey & Wickens, 2006; Preece et al., 1999) and texting (Hosking et al., 2009) on driving performance. The effects of orthopedic procedures including treatment of lower extremity fractures (Carmont, 2004; Egol et al., 2008; Egol et al., 2003), total knee arthroplasty (Hau et al., 2000; Marques et al., 2008), anterior cruciate ligament reconstruction (Gotlin et al., 2000), and total hip arthroplasty (Ganz et al., 2003; MacDonald & Owen, 1988) have also been investigated.

Statistical models have been developed to characterize driving ability in patients that have suffered a stroke (Akinwuntan et al., 2006; Nouri & Lincoln, 1993), brain disorders (Innes et al., 2007) and other traumatic brain injuries (Sommer et al., 2010). Most of these studies measured perceptive-cognitive tasks and used logistic regression models to correlate them with results from on-road driving assessments. However, these models only predicted binary results, pass or fail.

The overall goal of this research is to develop a mathematical model that will accurately predict a driver's reaction speed for patients that undergo a variety of different orthopedic procedures and to evaluate patients with neurological or neuromuscular deficits (e.g., brain disease, brain tumors, stroke, Parkinson's disease, traumatic brain injury) to provide information about driving capability. In this study cognitive challenges and physical impairments were imposed and their effect on cognitive, neuromuscular, and total reaction time was evaluated. From these measured results; we developed a linear mathematical model that may be used to quantitatively predict drivers' performance over a variety of possible driving conditions. Predictions were not limited only to conditions tested, but also included linear combinations of these test conditions. We believe that this is the first model to use this linear combination approach to predict drivers' reaction speed.

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Methods

Subjects

Twenty-four (8 female, 16 male) participants from the university and surrounding area volunteered to participate in the study. Participants were included into the study based on the following criteria: (1) Subjects were considered apparently healthy and had no recent history of either cognitive or neuromuscular injury or illness that limited driving ability; (2) Subjects were experienced drivers with at least four years of driving experience and had a valid driver's license; (3) Subjects owned a cell phone and each had experience text messaging. Subjects were arranged into two groups. Group one [24.2 (2.9) years, 1.78(0.09) m, 77.4(14.8) kg] was tested to evaluate the effects of dual cognitive tasks on driving reaction speed, where hand held cell phone talking was selected as the primary test parameter and texting as secondary. Group two [25.1 (2.0) years, 1.73(0.09) m, 77.4(14.8) kg] was tested to evaluate the effects of a physical impairment on reaction speed, with the impairment being a fixed knee brace. Group two was also used for model verification.

Driving Reaction Speed Test

All trials were performed on a custom-built driving reaction speed tester (DRST). The DRST was designed to replicate the cockpit of a vehicle and included an adjustable seat, a steering wheel, and gas, brake, and clutch pedals (Figure 1a). The seat and steering wheel distances were adjustable to allow subjects of all heights to be comfortably positioned within the DRST. The test was controlled using a custom virtual instrument created using LabView software (National Instruments; Austin, Texas). A monitor was positioned in front of the driver to provide instructions for the driver (Figure 1b). Green and red lights were used to instruct the driver to depress the gas or brake pedal, respectively. At the beginning of each trial the green light was illuminated instructing the driver to depress the gas pedal. At a random time between 8 and 12 s, the light changed to red indicating that the driver should press the brake pedal. The sequence of red and green lights was alternated at random 8–12 s intervals. Participants were instructed to place their hands on the steering wheel during driving, but no steering was required. A data acquisition card (NI 630505398; National Instruments, Austin, Texas) installed in a personal computer was used to record (1000 Hz) the voltage associated with the positions of the gas, brake, and clutch pedals. Visual feedback of foot pedal position was also provided to the driver on the display. Indicator bars for the clutch, brake, and gas pedal were used to show how far each pedal was depressed in real time. Following each trial, the LabView program saved the results of the trial to a file. After testing was completed, the test files were accessed using Matlab software (MathWorks; Natick, Massachusetts) and the reaction speeds were calculated.

The full braking time (FBT) was decomposed into three components: cognitive reaction time (CRT), foot movement time (FMT), and break travel time (BTT) (Egol et al., 2003). The CRT indicated the time needed for the participant to respond to the change in indicator light from green to red and begin foot movement. The FMT was defined as the time required to release the gas pedal and to make contact with the brake pedal. The BTT was defined as the time needed to fully depress the brake pedal after initial brake pedal contact. The full braking time indicated the amount of time needed to achieve maximum braking force.

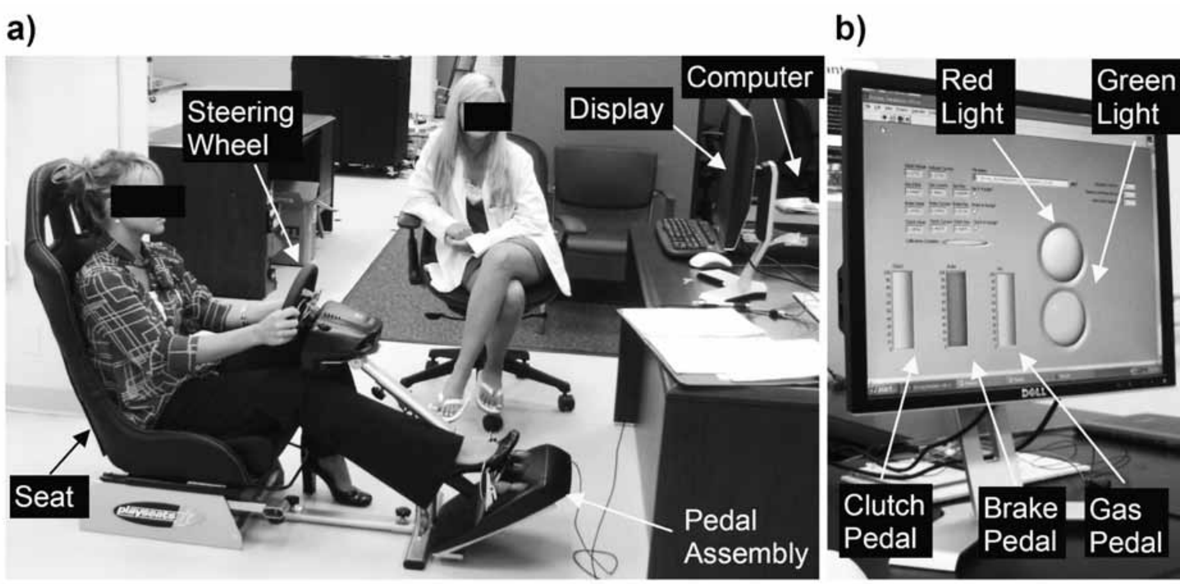

Figure 1 — Driver reaction speed tester (DRST). (a) Simulates a motor vehicle cockpit with an adjustable seat, steering wheel, and gas, brake, and clutch pedals. (b) Driver follows directions provided on the display screen including "go" (green light) and "stop" (red light) indicator lights and bars display the current state of foot pedal depression.

Experimental Procedures

Group one (n = 12) performed three separate reaction speed tests: normal, cellular talking, and text messaging. This group was used to measure changes in cognitive reaction speed associated with distracted driving (or dual tasking). Before testing, three practice tests were performed to reduce learning effects. Participants were instructed to fully depress the gas pedal when the light was green and to quickly move the foot to the brake and fully depress the pedal when the light turned red. During the test, the light was initially set to green and randomly switched between green and red at 8–12 s intervals. Trials lasted 60 s with most trials having three green to red transitions.

The order of testing was randomized and counterbalanced with half of the subjects tested first while talking on a cell phone, followed by testing under normal driving conditions. In all cases the texting trials were performed last. Both practice and normal tests had no distractions and only required the subject to react to a green light changing to a red light located on the computer screen. During the cellular talking conditions, subjects reacted to the same stimulus as in the practice and normal conditions but were asked to answer questions given to them by a study investigator (Table 1) through their cell phone. Subjects were instructed to answer each question as quickly as possible and if the answer was not known they were instructed to say, “I don’t know.” For the text messaging condition, up to 30 messages were sent to each subject before the beginning of the test. Participants were instructed to text answers to each text message as quickly as possible while simultaneously reacting to the stimulus from the DRST.

A separate subject group, group two (n = 12), performed two separate reaction speed tests: normal and fixed knee brace (FKB). This group was used to measure changes in musculoskeletal reaction times associated with a physical impairment. In addition, data collected from this group was also used for model verification. As before, three practice trials were administered before testing and a block randomization of normal and FKB conditions was used to determine testing order. The FKB condition was performed with the right knee fixed in a knee brace at approximately zero degrees of flexion. Furthermore, group two performed one additional reaction speed test; FKB with cellular talking. This test condition was not used in the development of the model, but was collected to evaluate the ability of the model to predict performances for untested conditions. All tests were administered the same way as with the first group except for the addition of the FKB.

Table 1 Sample of cell phone questions

A: Sample of Cell Phone Talking Questions
How many days are in the month of July?
Find the square root of 144, then multiply x 2
What is the capitol of North Carolina?
How many times does 10 go into 500?
What is the season after winter but before summer?
Who is our current vice president?
Name the cardinal directions.
Count down from twenty by fours.
B: Sample of Cell Phone Texting Questions
List three fast food restaurants.
List the 5th, 6th, and 7th months of the year.
Name two in-state private universities.
List three natural disasters.
What are three items of clothing?
What are the four days after Tuesday?
What are three common professions?
What colors mix together to make green?

Data Analysis

Voltages indicating the state of the red and green instruction lights, and the gas, brake, and clutch pedal positions were imported into Matlab as a time series. A threshold detection method was used to determine when the light changed from green to red. This was done by searching the time series to detect the first occurrence when the voltage for the red light (indicated by “x” in Figure 2a) exceeded 0.1 V, indicating a change in the lights from green to red. This index value, I_{A0}, (9117 ms) represents the beginning of the first reaction speed test within the trial. Next, the voltage of the green light (indicated by “o” in Figure 2a) was searched to detect the first time it exceeded 0.1 V after the initial light change, indicating a change in the light from red to green and preparation for the next test (17,320 ms). This method was repeated to find the other transition times and to determine the index values in the time series representing the beginning of each reaction speed test I_{A0}, I_{B0}, and I_{C0} (9,117 ms, 25,920 ms, and 49,619 ms).

A subset of the data beginning at the first index number, I_{A0}, and ending at, I_{B0}, was created to define the first reaction speed test within the trial. Data before and after the index values were cropped so that the subset only include the data between the index values. This process was repeated for each reaction speed test within the trial, typically three. Thus, the first data point in each subset corresponded with the changing of the light from green to red for each respective reaction speed test within the trial. The pedal position was plotted for these three time series (Figure 2b). The time of gas pedal release, I_{A1}, was calculated by searching for a drop in pedal voltage below 99% of the average gas pedal voltage over the first 100 ms. This tight threshold was possible because the gas pedal voltage typically had fluctuations less than 2 mV. The time when full braking occurred, I_{A3}, was calculated by searching for the first time the brake pedal voltage exceeded 95% of the average brake pedal voltage over the last 100 ms before the analysis cut off time (i.e., the full-scale voltage). The analysis cut off time was set to 3000 ms past the time the light changed

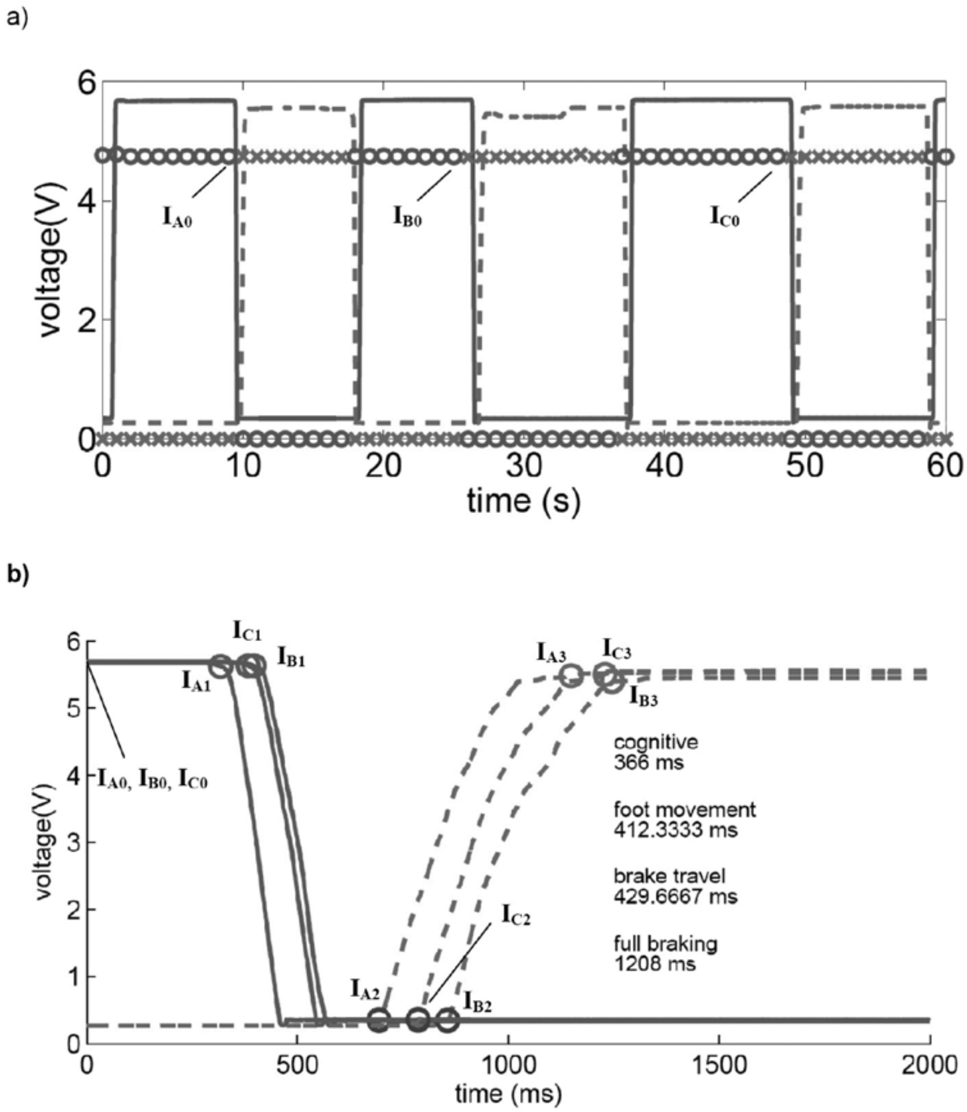

Figure 2 — Reaction speed data. (a) Indicator light and pedal voltages were stored as a continuous time series over the 60 s trial. IA0, IB0, and IC0 mark the beginning of each individual reaction speed test within the trial, where the first subscript indicates the individual test, A, B, or C. (b) These index locations were used to decompose the continuous time series into individual reaction speed tests that were plotted with a common origin based on the change of the indicator light from green to red. The second subscript, 1, 2, or 3, indicate the end of the cognitive, foot movement, and brake travel portion of the reaction speed test, respectively.

from green to red. This was chosen to allow adequate time for reactions under all testing conditions, yet be sufficiently far from the beginning of the next test or the end of the time series. The reduced cut off value of 95% of full scale was selected because brake depression voltages were less consistent than for the gas pedal. The initiation of braking, I_{A2}, was found by searching for the first incidence of brake pedal voltage above 1% of the full scale braking voltage found earlier. These indices were used to calculate the component of reaction speed,

$$\mathrm{CRT}_i = I_{i\,1} - I_{i\,0} \tag{1}$$

$$\mathrm{FMT}_i = I_{i\,2} - I_{i\,1} \tag{2}$$

$$\mathrm{BTT}_i = I_{i\,3} - I_{i\,2} \tag{3}$$

$$\mathrm{FBT}_i = I_{i\,3} - I_{i\,0} \tag{4}$$

where CRT_i, FMT_i, BTT_i, and FBT_i are the reaction speed for test, i, corresponding to test A, B, or C. The mean value for the tests is displayed on the plot (Figure 2b) and represents the results of the 60 s trial.

A one-way ANOVA was used to determine the individual effect of cell phone talking, cell phone texting, and a fixed knee brace on CRS, FMT, BTT, and FBT.

An independent *t* test was used to evaluate differences between groups. All statistics were analyzed using SPSS software (SPSS Inc.; Chicago, Illinois) with significance set as $p < .05$ for all tests.

Mathematical Model

A linear mathematical model was developed to predict the reaction speed under various testing conditions. The predicted full braking time, *PT*, for a specific set of test conditions was,

$$PT = N_j + \sum_{m=1}^{n} A_m + \sum_{m=1}^{n} B_m + \sum_{m=1}^{n} C_m \quad (5)$$

where N_j is the average FBT under normal conditions for participant *j*. The terms A_m, B_m, and C_m are the effects of each modifier on the CRT, FMT, and BTT, respectively. The applied modifying factor is *m,* and *n* is the total number of modifying factors. In this study, conditions primarily affecting cognitive reaction speed were talking ($m = 1$) or texting ($m = 2$) on a cellular phone. The main modifier associated with musculoskeletal reaction speed was the physical impairment of a FKB ($m = 3$).

Results

Analysis of the experimental data for group one using a repeated measures one-way ANOVA revealed that there were significant differences in CRT between the three driving conditions ($p < .001$). Mean (*SD*) CRT for normal driving was 362 (38) ms, talking on a cell phone was 484 (59) ms, and texting was 630 (154) ms (Figure 3). A pairwise comparison showed that talking increased CRT by 122 ms ($p < .001$), an increase of 34% and texting increased CRT by 268 ms ($p < .001$), an increase of 74%. FMT also changes significantly ($p = .013$) with 268 (57) ms for normal driving, 264 (68) ms for talking on a cell phone, and 302 (64) ms for texting. A pairwise comparison showed that talking decreased the FMT by 4 ms ($p = .68$) but the difference was not significant. Texting increased the FMT by 34 ms ($p = .028$). Differences in BTT were not significant ($p = .125$) with mean values for normal driving being 199 (80) ms, talking on a cell phone being 199 (79) ms, and texting being 223 (86) ms. Although the differences were not significant at the a = .5 level, pairwise comparisons showed texting increased BTT by 24.8 ms ($p = .114$). The FBT was significantly affected by the testing conditions ($p < .001$) with mean values of 829 (141) ms for normal driving, 947 (173) ms for talking on a cell phone, and 1156 (228) ms for texting. A pairwise comparison showed that talking increased the reaction time by 118 ms ($p = .002$), an increase of 14% and texting increased the reaction time by 327 ms ($p < .001$), an increase of 39%.

For group two, a repeated measures one-way ANOVA was also performed. Significant differences in CRT was not observed between the two driving conditions ($p = .074$), with a mean value of 322 (36) ms for normal driving and 338 (45) ms with a fixed knee brace (Figure 4). Using a FKB increased FMT by 49 ms ($p = .002$) from 250 (61) ms to 299 (76) ms, an increase of 20%. The FKB also increased BTT by 55 ms ($p = .013$) from 184 (56) ms to 239 (53) ms, an increase of 30%. These differences significantly increases FBT by 120 ms ($p = .002$) from 756 (128) ms to 876 (140) ms.

An independent *t* test was used to determine if there were significant differences between the means of the reaction speeds for both groups under the normal condition. The CRT for group one was found to be 40

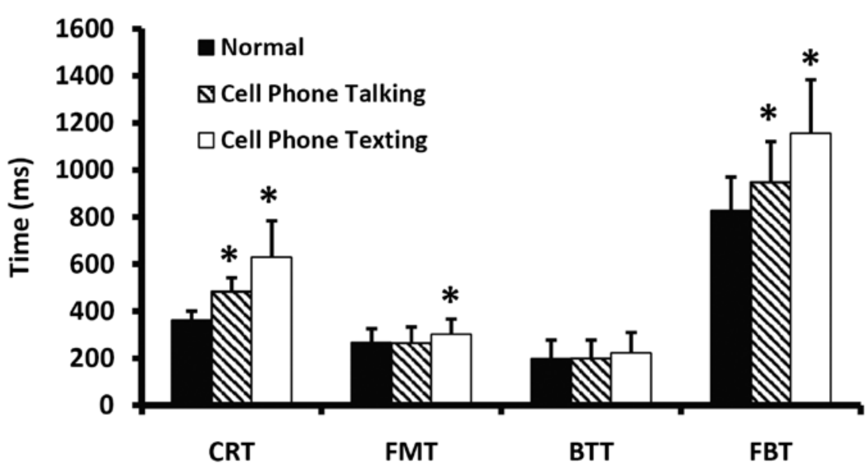

Figure 3 — Group one results show how cell phone talking and texting affect the individual components of reaction speed. A significant difference between the test condition and normal is indicated (*).

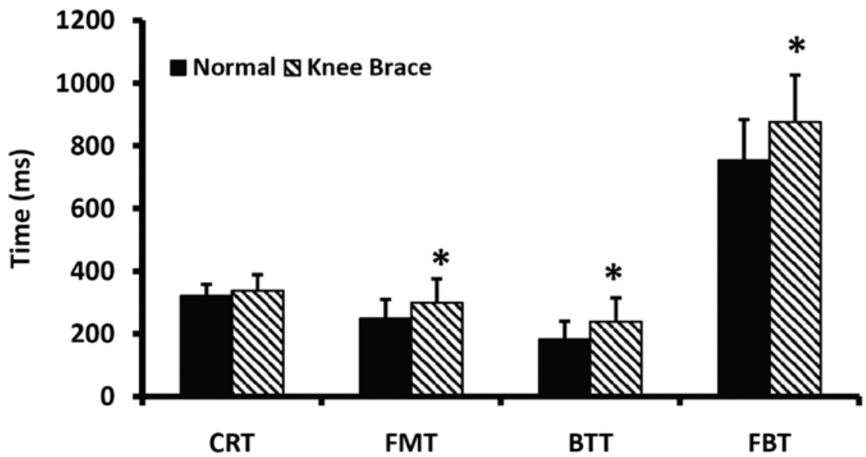

Figure 4 — Group two results show how a fixed knee brace affects the individual components of reaction speed. A significant difference between the test condition and normal is indicated (*).

ms greater than group two (p = .015). There were no differences in FMT (p = .447), BTT (p = .603), or FBT (p = .199).

The effect of each test condition obtained from experimental data were used to generate the calibration parameters (Table 2) for the mathematical model. The value for each modifying factor was found by subtracting the mean value for normal driving from the mean value of the result found for the modified condition. Parameters that were found to be statistically significant were used directly in the analysis. Those parameters that did not show a significant difference were individually assessed. The effect of cell phone talking on FMT was a decrease of 4 ms. Since it was only 32% likely that the difference was not due to chance (p = .68), the effect of cell phone talking on FMT value was assumed to be zero. The effect of cell phone talking on BTT showed no difference when rounded to the nearest millisecond so a difference of zero was used. The effect of texting on BTT was an increase of 24.8 ms. Although this difference was not significant at a=0.05, there was an 88.6% chance that the difference observed was not due to chance alone. Because the probability that this effect was real was much higher than the chance that it was due to random differences, it was included in the model. The final modifier needing evaluation was the effect of a FKB on CRT. The 16 ms increase CRT (p = .074) was 92.6% likely to not be due to chance alone and was included in the model.

The linear model (Eq. 5) was used to predict full braking time for a previously unevaluated test condition, the reaction time for talking on a cellular phone with a fixed knee brace (Figure 5). The model predicted CRT to increase by 138 ms, FMT by 49 ms, and BTT by 55 ms. Model verification was performed by comparing the predicted results to those collected experimentally. Recall that participants in group 2 were tested under this specific condition to collect data for model verification. The test results were not used in the development of the model so that they could be considered independent. In addition, they were always collected after testing for the normal and FKB was completed.

Applying these modifiers to the mean values for group 2 resulted in predicted reaction times of 460, 299, 239, and 998 ms for CRT, FMT, BTT, and FBT, respectively. Actual experimental values showed a mean value of 507, 317, 208, and 1032 ms for CRT, FMT, BTT, and FBT, respectively. Model error was 9% for CRT, 6% for FMT, –15% for BTT, and 3% for FBT.

Table 2 Mathematical model calibration parameters

Condition	Symbol	Reaction Speed Cost
Cell Phone Talking	A_1	122 ms
	B_1	0 ms*
	C_1	0 ms*
Cell Phone Texting	A_2	268 ms
	B_2	34 ms
	C_2	25 ms*
Fixed Knee Brace	A_3	16 ms*
	B_3	49 ms
	C_3	55 ms

*Differences not significant at α = .05.

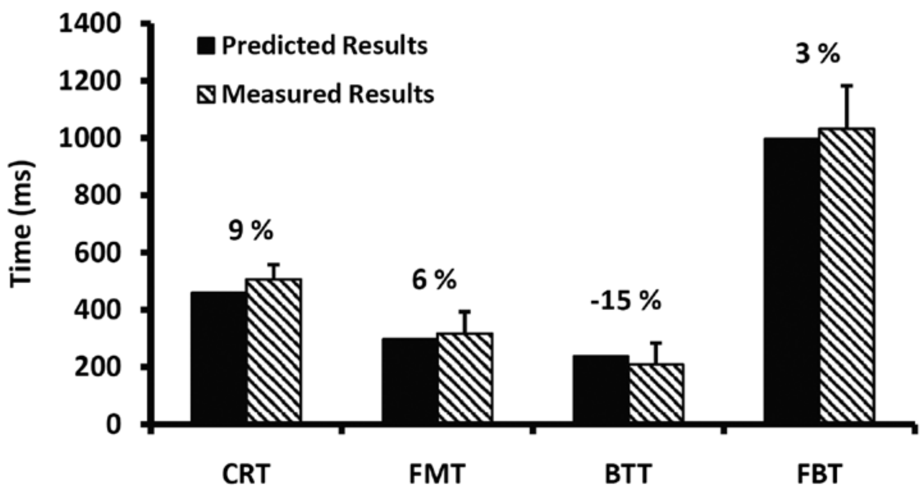

Figure 5 — Comparison of model predicted and actual measured results for drivers' reaction time. The linear model was able to predict the full braking time within 3% of the actual measured value.

Discussion

In this study a driving reaction speed tester was developed to study the effect of various driving conditions on reaction speed. Cognitive distractions and physical impairments were tested. The results showed that cognitive reaction times increased when using a cellular device, especially when texting. We expected to see no difference in the neuromuscular reaction speed between test conditions. This prediction was true for cell phone talking, but significant neuromuscular delays were associated with texting. It may be that texting requires more attention than talking since adults have been talking far longer than texting. Overall, the full breaking reaction time of texting is the slowest. This result supports recent legislation that prohibits cell phone texting while driving in many U.S. states (NHTSA, 2010).

Hands-free cell phone talking was not investigated in this study, but previous research has shown no advantages in using a hands-free vs. a handheld cell phone on driving performance while talking (Consiglio et al., 2003; Horrey & Wickens, 2006; McEvoy et al., 2005; Strayer & Johnston, 2001). This disadvantage in cell phones on driving performance, hands free or not, is suggested by Consiglio and colleagues to be due to interference in the capacity for attention (Consiglio et al., 2003). The results from this study support this finding.

It was expected that the use of a fixed knee brace would not affect cognitive reaction speed. This was found to be true using statistical tests ($p = .074$), but it was included in the model due to the high likelihood (92.4%) that the effect was real. Further testing with a greater number of subjects is needed to better understand this effect. Neuromuscular reaction time was increased by this physical impairment, with increases in both the foot movement time and brake travel time. These results were consistent with previous research showing that an orthopedic immobilization device can increase reaction times in driving simulations (Tremblay et al., 2009). Visual observations of participants using the FKB indicated that the FKB forced the participants to adopt a different strategy for braking that increased hip movement and ankle movement to compensate for a lack of knee flexion.

Logistic regression models have been developed to predict pass or fail occurrence in on-road driving assessments using a variety of parameters that influence perceptual-cognitive ability (Akinwuntan et al., 2006; Innes et al., 2007; Mazer et al., 1998; Nouri & Lincoln, 1993; Sommer et al., 2010). These models are useful to clinicians and researchers for making predictions about an individual's overall driving ability before actual road driving. However, these statistical models are not able to predict a person's driving capability under a previously untested driving condition such as following total knee arthroplasty. The linear model developed in this paper is able to predict reaction speeds for these types of orthopedic and neurological deficiencies.

The model was accurate and was able to predict cognitive reaction speed and foot movement time within 10%. However, the prediction for brake travel time was 15% slower than that found experimentally. This difference may be due to a learning effect. Because the validation test was always performed after the 10 randomized trials of "normal" and FKB, participants gained the experience of braking with a FKB, which they may have used to improve reaction speed over the trials used for model calibration. Overall, the model predicted full braking time within 3% of the measured value.

One limitation of this study is the use of a linear model. As a result, it cannot account for complex interactions that may occur between modifying variables. These interactions will be introduced into future nonlinear models when more data are available for model development. In addition, little information is known about the effect of learning under various testing conditions. Future studies should investigate these effects. This knowledge will be important when developing nonlinear models that may improve the accuracy of predictions. It is also worth noting that this test evaluates the time to achieve full braking and that additional time will usually be needed to stop the vehicle. Furthermore, the results for cell phone talking apply to answering challenging questions and may not be indicative of casual conversation. These qualifiers should be taken into account when using the values presented in this paper.

An additional limitation of this study was that the experience level of texting was not quantitatively defined. Subjects self reported that they had experience with sending and receiving text messages, but no evaluation of texting capability was assessed. This may partially explain the large standard deviation observed in the cognitive reaction time for texting.

This paper presents a mathematical model that may be used to predict driving reaction speed for a variety of influencing conditions. Although only a few influential conditions were evaluated, we present a general approach that may be expanded to include other types of distractions, impairments, and environmental conditions.

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