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Steering-wheel grip force characteristics of drivers as a function of gender, speed, and road condition

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Abstract

This paper presents the results of a steering-wheel grip force study of male and female drivers driving an automobile on two different road conditions (smooth and rough asphalt) at two different speeds (45 mph = 72 km/h and 65 mph = 105 km/h). Thirteen subjects (males and females) participated in this study. The force measurements were made through a custom-made capacitive pressure mapping system wrapped around the steering wheel. Results indicated significantly higher absolute force and net grip force values for the male drivers in comparison to the female drivers. On the other hand, the vehicle speed and the road condition did not significantly affect these response variables. In comparison, the relative value of the driver steering-wheel grip force, expressed as a percentage of the maximum voluntary steering-wheel grip force, and the net relative value of the driving steering-wheel grip force, expressed as a percentage of net maximum voluntary steering-wheel grip force, were not affected significantly by any of the factors. The drivers, on the average, applied their 31% of maximum voluntary steering-wheel grip force, and 21% of net maximum voluntary steering-wheel grip force, intermittently, to the steering wheel, while driving. The capacitive pressure mapping system was found to be a useful method in determining and monitoring the drivers' grip force while driving.

Relevance to industry

The knowledge of steering-wheel grip force characteristics of the drivers may benefit the automobile designers and manufacturers to improve the quality of their products in terms of comfort and driving performance. This study used a capacitive pressure mapping system in obtaining such information and presented the drivers' grip force characteristics for a sample of drivers.

Keywords: Steering-wheel grip force; Steering system design; Pressure mapping system; Driver grip strength; Driver characteristics; Automobile design

1. Introduction

Information on drivers' steering-wheel grip force as a function of road condition, speed and gender, and an effective grip force measurement system may be useful to the designers of vehicles, especially to the designers of steering systems and researchers, from several perspectives. Firstly, to accurately quantify the effect of grip force on a driver's annoyance response of steering-wheel vibration, the magnitude of grip force needs to be controlled. Secondly, since the mechanical characteristics of the steering system, such as modes and damping, are affected by the hand contact on the steering wheel, a simple and robust method to monitor the grip force may be of great help to the engineers who are investigating this aspect. Thirdly, steering-wheel optimal dimensions and surface cover materials may be studied more accurately with the knowledge of grip force behavior of the drivers. Furthermore, driver performance and comfort responses may be studied more accurately, if the steering grip force is introduced into the performance and comfort equations as one of the independent variables.

For the measurement of grip force, the traditional approach is the use of strain gages (Pyykkö et al., 1976; Reynolds, 1977; Burström et al., 1994; Gurram et al., 1995;

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Haasnoot and Mansfield, 2004). This approach, however, requires a specially constructed steering wheel with strain gages applied to the cross-section. In addition, the durability of the strain gage system is limited due to the delicacy of the strain gages. Consequently, although feasible for specialized laboratory experiments, the use of strain gage lacks the aspect of practicality in most of the steering-wheel applications.

Owing to the stated drawbacks of strain gauges, this study used an alternative method. In this method, a pressure pad composed of a number of pressure sensors was placed between the steering-wheel surface and the driver's hand to measure and monitor the steering-wheel grip force. Unlike the strain gages, the pressure pad does not require a custom steering wheel. In addition, it is portable, durable, and easy to use. Hence, the pressure pad can be used virtually on any steering wheel for the measurement of the steering-wheel grip force in real-life driving conditions with minimal interference with the driver.

The use of pressure sensing elements to obtain the pressure distributions is not new. Pressure sensing elements arranged in a matrix configuration have been used for ergonomic optimization of the design of vehicle seats (e.g., Shiratori and Ishida, 1992) and also for measuring pressure distribution over a steering wheel (Maggiorana et al., 2001). There are several types of pressure sensors. Among them, the film sensors are very commonly used for their great advantage of size. They are based on piezo-polymer, capacitive, conductive-ink, or resistive polymer sensing elements. At present, they have many metrological problems mainly due to nonlinearity, rheological behavior, dynamic characteristics, mounting surface shape and curvature, data acquisition system, etc. Piezo-polymer sensors have the limitation of capturing very slow pressure fluctuations or static pressure components. Sensors based on conductive ink or resistive polymers show metrological characteristics that change in time and exhibit a remarkable hysteresis. Among those, capacitive sensing elements are found to be the most suitable because of their capability of measuring both dynamic and static pressure with acceptable linearity and hysteresis (Maggiorana et al., 2001; Fergenbaum et al., 2003). Hence, the pressure sensors with capacitive sensing elements were the choice of this study.

The related research reviewed consisted of only a single study, Maggiorana et al. (2001), on measuring the steering-wheel grip pressure distribution, with some preliminary results. Maggiorana et al. used a pressure measuring system with capacitive sensing elements (Novel GmbH, Munich, Germany) to measure grip pressure distribution at the operator's hand/car steering-wheel interface. Their main aim was to test the reliability of such system in determining steering-wheel grip pressure distribution. They have concluded that such measurement system is reliable and suitable for evaluating steering grip force distribution in on-road tests. They have also reported three different grip pressure levels: 5 kPa (in normal driving condition on a straight way), 10 kPa (during a turning phase), and 30 kPa (in critical driving conditions as a sudden brake or fast pickup). However, they did not report the mean steering force values, and any detailed statistical results related to the pressure distribution or grip force characteristics of drivers.

For the present study, it was hypothesized that gender, road condition and speed were the most important factors that could affect the magnitude of a driver's steering-wheel grip force. The main objective of this study, therefore, was to investigate the grip force characteristics of the drivers, both male and female, under varying speed and road condition. Another objective of the study was to evaluate a capacitive pressure mapping system as a valid grip force measurement system.

2. Methods

2.1. Test apparatus

A full-size passenger car (2005 Ford Taurus Sedan, V6, 3.0L engine, automatic transmission) was used as the test vehicle. The steering wheel was a 4-spoke design, wrapped in leather (without stitches), and had a cross-section with a circumference of 100 mm (~32 mm diameter). The outside-to-outside wheel diameter was 380 mm.

A custom-made XSensor® X2 Pressure Mapping System (XSENSOR Technology Corporation, 2003) with a pressure distribution pad was used to measure the grip force in this study. The X2 system uses polymeric-capacitive film sensors. They are made of a sandwich structure realized by deposition of two metal layers on two polymeric substrates. Each of them acts as one armature of a capacitor, whose dielectric material is silicon rubber. A pressure change causes a sensor compression and capacitance variation. The capacitance value is read by a modulator–demodulator circuit. Each of these cubic sensors had the dimensions of $7\,mm \times 7\,mm \times 1\,mm$ in length, width and thickness, respectively. The pressure pad with a $180\,mm \times 105\,mm$ effective sensing area was composed of a matrix of 390 pressure sensors (26 sensors in length and 15 sensors in width). The pad can be used in a pressure range of 0–50 psi. The measurement system records the immediate pressure distribution on the pad as frames with a recording speed of up to 10 frames/s.

For the measurement of grip force response, the pressure pad was wrapped around the steering wheel at 2 o'clock location (Fig. 1). It was secured on the steering wheel using a duct tape on both sides of the pad. The pad cable was hanged from the top of the headliner in order to minimize the interference with the driver. The cable was long enough to allow full steering-wheel rotation. For the measurements, the calibration file supplied by the manufacturer for a 1–50 psi calibration range was used. The grip force was calculated by a custom-written software by multiplying the

Fig. 1. Location and placement of the pressure pad for testing.

Table 1
Descriptive statistics of the subject population

	Mean	Std. dev.	Median	Range
Males ($n = 8$)				
Age (yrs)	27.5	7.4	24	22–43
Height (cm)	178.0	6.0	178.5	165–183
Weight (kg)	73.9	10.8	70.5	62.5–90
Females ($n = 5$)				
Age (yrs)	26.6	2.2	26	24–30
Height (cm)	163.6	5.4	162	160–173
Weight (kg)	53.4	3.4	63	50–59
Combined ($n = 13$)				
Age (yrs)	27.2	5.8	26	22–43
Height (cm)	172.5	9.2	176	160–183
Weight (kg)	66.0	13.4	65	50–90

average pressure by the total area of active sensors at a given frame.

The drivers were keeping their right hands (all subjects were right-handed) between the indicated white lines (active sensor area) on the pressure pad for accurate measurements. The pad was wrapped flexible enough on the backside to allow the drivers to use their fingertips to contribute to the grip.

2.2. Participants

Thirteen drivers (eight males and five females) participated in the study. All participants were experienced drivers. The descriptive statistics of the driver population is given in Table 1.

2.3. Test protocol

The drivers were asked to sit on the driver seat. They were reminded to adjust the seat and the mirrors and they were allowed to tilt the steering wheel for their comfort. The subjects wearing any jewelry on the right-hand fingers were asked to remove them, since the metal could interfere with the pressure sensors. Then, they were asked to take the gripping position of the wheel, placing the right hand on the pressure pad between the two white lines (Fig. 1) and the left hand at 10 o'clock position of the wheel. It was observed that all of the drivers preferred bent-arm position.

A description of the route they would follow was given to the drivers; however, no details of the objectives of the experiment were provided to minimize the probability of any bias that could occur. They were instructed to drive the car as they would drive their cars everyday.

Before the beginning of the driving task, the rest force (F_{rest}), and the maximum voluntary steering-wheel grip force (F_{max}) were recorded for each driver. For F_{rest} measurement, the driver was instructed to grasp the steering wheel without pushing, pulling, or squeezing it, but simply resting the hand on the wheel while holding the grasping position. The load on the pressure pad at this resting position was recorded as F_{rest}. F_{rest} was mostly a function of a driver's arm weight. For F_{max} measurement, the driver was instructed to grip the steering wheel with both hands and exert squeezing force on the wheel as much as he or she could without pushing or pulling the steering wheel. The driver was required to rise to his or her maximum grip force in about one second without jerking, and hold the maximum grip force for four seconds following the Caldwell protocol (Caldwell et al., 1974). The right-hand value of the driver was recorded as F_{max}. F_{max} and F_{rest} recordings were repeated twice. If the values were not within 5% of each other, than the additional tests were performed. For the F_{max} the maximal and for F_{rest}, the average value of the measurements was recorded as valid F_{max} and F_{rest}, respectively. There was a 3 min rest period between two successive trials to eliminate the fatigue effect on force production. These baseline measures were used for obtaining the relative response measures as described in Section 2.4.

The drivers were allowed to drive the car for a few miles to get used to the car and the equipment, and relax before the actual data collection. The use of the car's cruise control was demonstrated to the driver. The driver followed the test-loop driving on a smooth city road, rough city road, smooth highway road, and rough highway road.

An 18-mile (~29 km) test loop was determined for the experiments. All the tests were conducted in daytime. Before noon and early afternoon times were preferred for the tests to avoid the potential heavy traffic. The data recording for the experiment was performed in sections of the test loop that fit to the description of the road condition. The cruise control of the car was used to set the speed to desired level before the data recording. The data collection with each driver took about 30 min. The total time burden of the experiment for each driver was about 1 h.

2.4. Statistical methods

A two-level, full factorial design for three factors, namely the 2^3 design, with 13 replications ($n = 13$) was used for the experiment. The three independent variables (factors), each with two levels, and the response variables are given in Table 2. The definitions of the response variables are as follows.

Absolute force (F_{abs}): It is a driver's actual steering-wheel grip force measured during on-road driving experiments corresponding to the each of the four road condition–speed combination. F_{abs} is composed of two components: the effort and arm weight. The other three response variables were calculated using F_{abs}, F_{rest}, and/or F_{max} values as described below.

Net grip force (F_{net}): It is obtained by subtracting F_{rest} from F_{abs} (Eq. (1)). That is, F_{net} is the effort component of F_{abs} (Eq. (1)):

$$F_{net} = F_{abs} - F_{rest}. \tag{1}$$

Percent of maximum force ($\%F_{max}$): It is a relative force measure defined as the ratio of F_{abs} to F_{max} (Eq. (2)):

$$\%F_{max} = \frac{F_{abs}}{F_{max}} \times 100. \tag{2}$$

Percent exertion (% Exertion): It is a relative measure of the magnitude of F_{net} applied on the steering wheel as a fraction of netF$_{max}$ ($= F_{max} - F_{rest}$) (Eq. (3)):

$$\%\text{Exertion} = \frac{F_{abs} - F_{rest}}{F_{max} - F_{rest}} \times 100 = \frac{F_{net}}{\text{netF}_{max}} \times 100. \tag{3}$$

It should be noted that both F_{abs} and $\%F_{max}$ include the effect of the arm weight on the pad (i.e., on the steering wheel); on the other hand, F_{net} and %Exertion do not.

For the comparison analysis of the data, if the assumptions (i.e., normality, independency, and homogeneity of variances) underlying the analysis of variance (ANOVA) were satisfied, parametric ANOVA were used. In case of lack of validity of the assumptions, rank transformations were performed. The usual ANOVA, then, were performed on both the ranked and original data. When the results of both procedures were similar (which was the case for the present study), it was judged that the ANOVA assumptions were probably satisfied reasonably well, and the standard analysis is satisfactory (Conover and Iman, 1981; Montgomery, 2001). Therefore, parametric ANOVA results performed on the original data are provided in this paper. Following the ANOVA, post-hoc testing was not required for significant main factor effects since all factors had only two levels and all interaction effects were nonsignificant. For all comparisons, $p<0.05$ was considered statistically significant. The statistical analysis was performed using MINITAB® Statistical Software (Minitab Inc., 2003).

Table 2
Experimental variables

Independent variables (factors)	Factor levels	Response variables
Gender	Male Female	Absolute force (F_{abs})
Speed	45 mph (72 km/h)-city 65 mph (105 km/h)-highway	Net grip force (F_{net}) Percent of maximum force ($\%F_{max}$)
Road condition	Smooth (asphalt) Rough (asphalt)	Percent exertion (%Exertion)

3. Results

The descriptive statistics of the response variables categorized by gender and driving conditions (road and speed) are presented in Tables 3 and 4.

3.1. Grip force with respect to gender

The descriptive statistics for the response variables F_{abs}, F_{net}, $\%F_{max}$, %Exertion, F_{rest}, and F_{max} for the males, females and combined driver population is provided in Table 3.

The boxplots and main effect plots for F_{abs} and F_{net} indicate a significant gender effect on both force variables with respect to both location and variation (Figs. 2 and 3). It can be observed from the plots that the male drivers, on the average, exert higher force values in comparison to the female drivers for both force variables. ANOVA results presented in Table 5 confirm this observation that the gender is the only factor significantly affecting F_{abs} and F_{net} (for F_{abs}: $p<0.0001$); and for F_{net}: $p<0.037$). The entire factor and the interaction effects are nonsignificant for all response variables: F_{abs}, F_{net}, $\%F_{max}$, and %Exertion. (A post-hoc test was not required for significant gender factor since it has only two levels).

The plots also indicate larger variation of F_{abs} and F_{net} for the males than for the females. These results are also presented in Table 3, which shows that the standard deviation of F_{abs} for the males is almost three times larger than for the females.

Table 3
Descriptive statistics of the response variables for the males, females, and combined subject population

Mean (std.)			
Response	Males	Females	Combined
F_{abs} (N)	66.3 (23.5)	42.7 (7.9)	57.8 (22.4)
F_{net} (N)	37.7 (16.6)	27.7 (9.8)	34.1 (15.2)
$\%F_{max}$	30.5 (9.1)	32.2 (5.8)	31.1 (8.1)
%Exertion	20.2 (8.9)	23.6 (7.9)	21.4 (8.6)
F_{rest} (N)	28.6 (15)	15.6 (5.8)	23.6 (13.6)
F_{max} (N)	223.7 (66.8)	135.1 (25)	189.6 (69.5)

Table 4
Descriptive statistics of the response variables for the tested conditions

Gender	Road condition	Speed (mph)	Response variable	Mean (std.)
Male	Smooth asphalt	45	F_{abs} (N)	60.1 (23.9)
			F_{net} (N)	31.5 (13.2)
			$\%F_{max}$	27.7 (9.0)
			%Exertion	17.1 (7.5)
		65	F_{abs} (N)	67.3 (23.9)
			F_{net} (N)	38.7 (18.3)
			$\%F_{max}$	31.4 (10.5)
			%Exertion	21.2 (10.8)
	Rough asphalt	45	F_{abs} (N)	71.4 (27.4)
			F_{net} (N)	42.8 (20.7)
			$\%F_{max}$	32.6 (10.6)
			%Exertion	22.6 (10.7)
		65	F_{abs} (N)	66.3 (21.9)
			F_{net} (N)	37.7 (14.6)
			$\%F_{max}$	30.3 (6.9)
			%Exertion	19.9 (6.7)
Female	Smooth asphalt	45	F_{abs} (N)	41.9 (9.9)
			F_{net} (N)	26.3 (12.3)
			$\%F_{max}$	31.2 (5.2)
			%Exertion	22.0 (8.0)
		65	F_{abs} (N)	43.8 (5.3)
			F_{net} (N)	29.7 (6.7)
			$\%F_{max}$	33.4 (5.7)
			%Exertion	25.5 (7.4)
	Rough asphalt	45	F_{abs} (N)	37.8 (6.1)
			F_{net} (N)	22.2 (7.4)
			$\%F_{max}$	28.3 (3.3)
			%Exertion	18.8 (5.3)
		65	F_{abs} (N)	48.7 (7.7)
			F_{net} (N)	34.6 (9.8)
			$\%F_{max}$	37.1 (6.9)
			%Exertion	29.6 (9.1)

The boxplots and main effect plots for the other two relative force response variables, $\%F_{max}$ and %Exertion, indicate slightly higher mean relative force values for the female drivers in comparison to the male drivers (Figs. 4 and 5). These results are also presented in Table 3. However, ANOVA results indicate no significant gender effect on these responses (Table 5).

For F_{rest} and F_{max} response variables, two-sample t-tests indicate significantly higher mean responses for the males in comparison to the females (for F_{rest}: $p<0.056$), and for F_{max}: $p<0.008$).

3.2. Grip force with respect to driving condition

The descriptive statistics of the response variables categorized for each of the four driving conditions are provided in Table 4. The results also are depicted in Figs. 3 and 5. Although slight, there is a tendency that rough road and high speed cause high grip force values. The rough asphalt—highway (65 mph = 105 km/h) driving condition is resulted in the highest mean value of all response variables, among the four driving conditions. On the other hand, the rough asphalt—city road (45 mph = 72 km/h) driving condition is resulted in the highest standard deviations for F_{abs} and F_{net}. For speed factor, the mean force ranges corresponding to 45 and 65 mph, respectively, are (N) F_{abs} (56–60), F_{net} (32–36), $\%F_{max}$ (30–32), and %Exertion (20–23). For the road condition factor, the mean force ranges corresponding to the smooth and rough asphalt, respectively, are (N) F_{abs} (56–59), F_{net} (32–36), $\%F_{max}$ (31–32), and %Exertion (21–22). Nevertheless, ANOVA results indicate no significant speed or road condition effects on these force responses (Table 5).

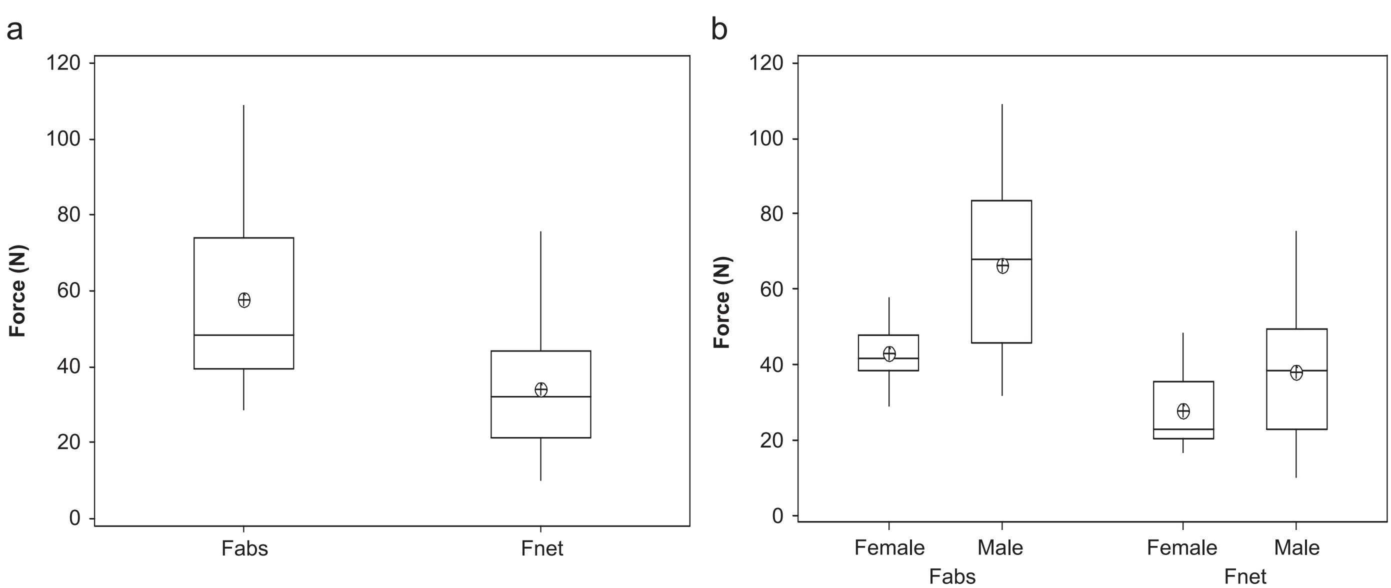

Fig. 2. Boxplots for F_{abs} and F_{net}: (a) whole subjects, (b) subjects categorized by gender. (The bottom and top edges of the box correspond to 25th and 75th percentiles, respectively. The line in the box corresponds to median value. The symbol (⊕) represents the mean. The tips of the lines on bottom and top of the box represent minimum and maximum values, respectively.)

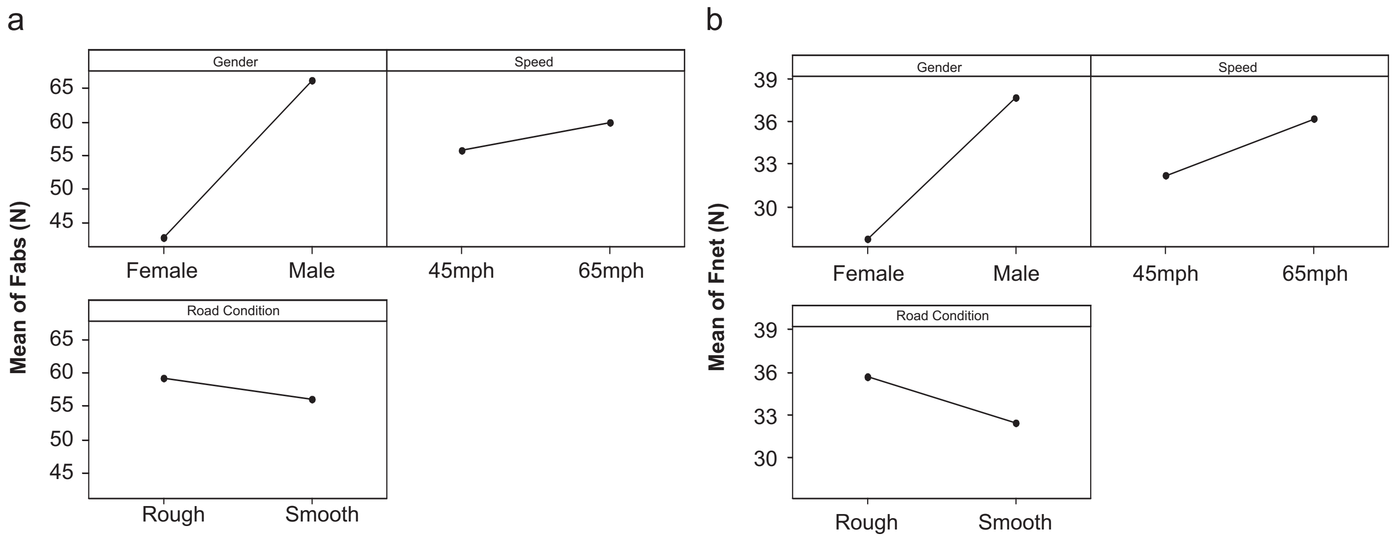

Fig. 3. Main effects for (a) F_{abs} and (b) F_{net}.

Table 5
Summary of ANOVA for the response variables

Factors and their interactions							
Variable	Gender	Speed	Road	Gender × speed	Gender × road	Speed × road	Gender × speed × road
F_{abs}	14.86 (0.000)*	0.38 (0.541)	0.22 (0.645)	0.19 (0.662)	0.16 (0.691)	0.02 (0.892)	0.78 (0.382)
F_{net}	4.65 (0.037)*	1.04 (0.314)	0.40 (0.529)	0.60 (0.442)	0.30 (0.586)	0.04 (0.852)	1.46 (0.234)
$\%F_{max}$	0.67 (0.419)	1.61 (0.211)	0.22 (0.644)	0.97 (0.329)	0.10 (0.758)	0.00 (0.958)	1.68 (0.202)
%Exertion	2.21 (0.145)	2.36 (0.132)	0.25 (0.617)	1.62 (0.211)	0.11 (0.742)	0.00 (0.973)	1.95 (0.170)

Numbers indicate F and p values.
*Effect of the factor is significant on the variable ($p<0.05$).

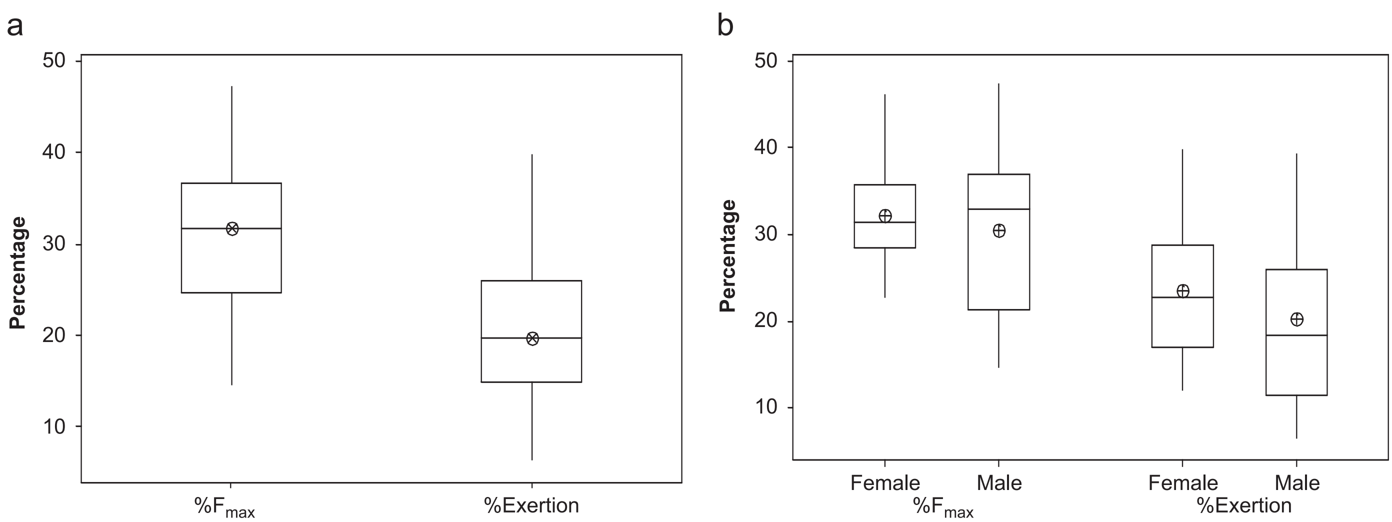

Fig. 4. Boxplots for $\%F_{max}$ and %Exertion: (a) whole subjects and (b) subjects categorized by gender. (The bottom and top edges of the box correspond to 25th and 75th percentiles, respectively. The line in the box corresponds to median value. The symbol (⊕) represents the mean. The tips of the lines on bottom and top of the box represent minimum and maximum values, respectively.)

4. Discussion

The statistical analysis results of this study indicate higher mean values of F_{rest} and F_{max} for the males in comparison to the females. This is an expected result since, on the average, arms of the males weigh more and maximum grip strength of males is higher than the females (e.g., Eastman Kodak Company, 2004; Chaffin et al., 2006).

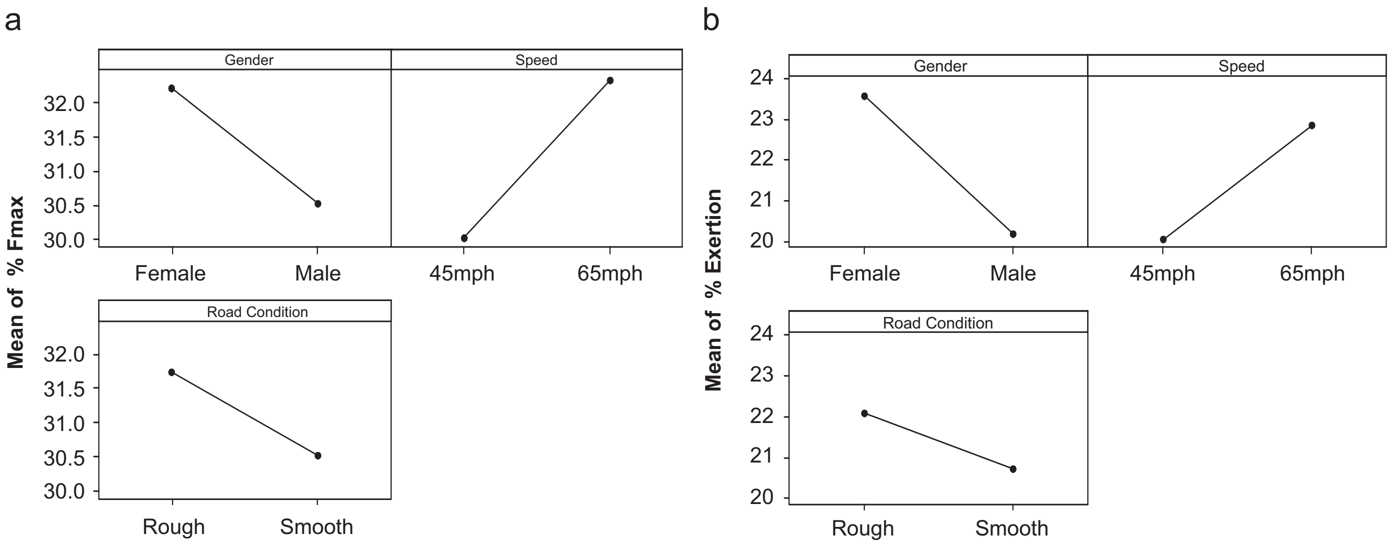

Fig. 5. Main effects for (a) $\%F_{\max}$ and (b) %Exertion.

The results also indicate that gender is the only statistically significant factor affecting the drivers' F_{abs} and F_{net}. For both responses, the mean force values of the male drivers are higher than the mean force values of the female drivers. A part of the higher mean value of F_{abs} for the males can be explained by the higher mean arm-weight component of the males. However, this trend is also true for F_{net}, which is only the effort part of F_{abs}, and thus cannot be explained by the higher male arm weight. Therefore, the rest of the difference may be attributed to the difference between the male and female driving behavior, the availability of the higher absolute strength capacity, and the sensory feedback from the muscles used. It may be hypothesized that due to the higher strength capacity, the male drivers may afford to exert higher absolute force values without feeling of discomfort in comparison to the female drivers.

For the relative steering-wheel grip forces, $\%F_{\max}$ and %Exertion, none of the factors (including gender) has significant effect on the mean of these relative response variables. The male and female drivers, on the average, apply a similar fraction of their maximal grip forces. This result may indicate that the steering-wheel grip force is a fixed percentage of maximum grip force, which does not change significantly between the genders for the tested experimental conditions. Considering only the effort part of the steering grip force (i.e., excluding the effect of arm weight), this value, on the average, corresponds to 21% of net$F_{\max}$ (%Exertion); and when the effect of arm weight is considered, then the value is 31% of $F_{\max}$ ($\%F_{\max}$). It is important, however, to note that the drivers apply these relative force levels intermittently but not continuously.

It was hypothesized and expected that the road condition and speed factors would affect the steering-wheel grip force response. Though there is a tendency that rough road and high speed cause higher grip force values, the differences are statistically nonsignificant. One explanation of this result may be the higher steering-wheel vibration caused by the rough road and high speed. The subjects possibly were uncomfortable by the higher vibration transmitted to their hands and tended to squeeze the wheel less strongly than they wanted to. In fact, several subjects indicated this.

The actual driving experiment lasted approximately 30 min per driver. Hence, the conclusions made from this study should be restricted to this short period only. If the driving distances and times were kept longer, say 3 h, "Would the subjects still exert the similar magnitude of force?" is a question that needs to be investigated.

It should be also emphasized that the current study involved a small number of subjects, thus the data presented in this study should not be considered as a normative data. To develop such normative data further studies with larger sample sizes need to be conducted.

A direct comparison of the results of this study, although desired, is not possible due to the fact the authors did not come across such steering-wheel grip force studies in the reviewed published research. However, below an indirect comparison of the data of the maximal steering-wheel grip force ($F_{\max}$) obtained in this study is made with another grip force study performed by instrumented cylindrical handles (Edgren et al., 2004). Edgren et al. reported the maximal grip force data using instrumented cylindrical handles with five different diameters (2.54, 3.81, 5.08, 6.35, and 7.62 cm). Their grip strength data obtained for the dominant hand using handles with 2.54 and 3.81 cm diameters was used to obtain an interpolated mean maximum grip force value for 3.2 cm handle diameter (i.e., diameter of the steering wheel in the present study). For the 3.2 cm handle diameter, the mean maximum grip force values for males (20–46 years of age range) and females (24–30 years of age range) were calculated as 284.3, and 181 N, from Edgren et al.'s, respectively. In the current experiment, the mean maximum grip force values for males (22–43 years age range) and females (24–30 years of age range) were 223.7, and 135.1 N, respectively (Table 3). The difference may be attributed to the differences in two experimental settings: (i) in the current experiment, the maximum grip force was applied with both hands simultaneously, whereas in Edgren et al.'s study, only one hand was used at a time; (ii) in the current experiment, the subjects were not asked to assume a specific arm posture, whereas in Edgren et al.'s study, the parameters to determine the body and arm posture were specified (i.e., the participants were sitting comfortably in a chair, the shoulder was adducted and neutrally rotated and the elbow was flexed at 90°, with the forearm and wrist in neutral position); and (iii) another factor maybe the shape of the steering wheel, which is circular in both diameter and perimeter, whereas the handles used by Edgren et al. were straight.

The steering-wheel grip force measurement procedure presented in this study is a promising method that has several advantages over the use of strain gages for the grip force measurement. The most important highlights of this method are the ease of use and durability of the pressure pad. When a strain gage is used to measure the steering-wheel grip force, it is placed on the cross-section of a customized steering wheel. In addition, the durability of the strain gage system is limited due to the delicacy of the strain gage. Thus, the use of strain gages is mostly limited to laboratory applications. On the other hand, the pressure pad can be used virtually on any steering wheel without customization to measure the steering-wheel grip force. In addition, the pressure mapping system is portable. Thus, it can be used safely in any vehicle in real-life driving conditions with minimal interference with the driver.

5. Conclusions

This study was conducted to collect steering-wheel grip force data from everyday drivers while driving in different road conditions and speeds. A custom-made capacitive pressure distribution pad wrapped around the steering wheel was used as the measuring device with a custom-written software. The results of this experiment showed that the males apply significantly higher absolute and net steering-wheel grip forces. However, both genders, on the average, apply similar relative grip forces for the all driving conditions studied. These relative force values, on the average, are $\%F_{\max} = 31$ and $\%\text{Exertion} = 21$.

The data obtained through this study, though not a normative data, may lead the way for further studies of driver–steering-wheel interaction. Knowing the grip force values, researchers can set realistic grip force levels for controlled simulator experiments and investigate the effects of grip force on, for example, hand–arm vibration transmission, comfort, and annoyance. The driving grip force data can help to investigate the mechanical characteristics of the steering systems, such as modes and damping, since these characteristics are affected by the hand contact on the steering wheel. The grip force measurement method introduced in this study can help the researchers to control and monitor the grip force levels. Another useful application area could be the design of comfortable steering wheels, which reduces contact pressure, thus the resultant grip force. Furthermore, driver performance responses could be studied more accurately, if the steering grip force is introduced into the equation as one of the independent variables.

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