

Evaluation of the Burden of Steering Wheel Switching Operation in an Ultra-Compact EV with Steer-by-Wire System

by

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Abstract

Owing to the compactness of ultra-compact electric vehicles (EVs), it is not satisfactorily install a mechanism for assisting steering, a power steering system, and other related systems. Therefore, a steer-by-wire system (SBWS) is being studied as one of the systems for assisting steering by the driver. However, there have been few studies on the physical burden and the driver's opinion when a steer-by-wire system is installed. In this study, we constructed a method for quantitatively evaluating the sense of burden when the driver continuously operates the steering wheel by conducting a questionnaire survey to determine the drivers' subjective evaluation of their sense of burden while operating the steering wheel and utilizing biological information obtained from electromyogram measurements. Furthermore, the relation between electromyogram measurement and subjective evaluation is considered. The results show that the subjects subjectively experienced a heavy burden when operating the steering wheel with one hand, and this tendency was also obtained from the measured muscle burden. Hence, it was determined that the switching operation is the most burdensome operation for the upper limbs of the driver.

Keywords: Ultra-compact electric vehicles, Steer-by-wire system, Subjective evaluation, Electromyogram

1. Introduction

In recent years, ultra-compact electric vehicles (EVs) are being increasingly sold by several automobile manufacturers, and are used as a transportation tool for traveling within a community area. In June 2012, guidelines for the introduction of ultra-compact mobility were presented by the Ministry of Land, Infrastructure, Transport and Tourism, thus increasing the attention directed towards ultra-compact EVs and their popularity for personal mobility. However, owing to their compactness, it is not satisfactorily install an assist mechanism for the steering operation, power steering system, and other related systems. Therefore, depending on the driving environment, steering wheel

operation becomes a burden. This leads to increasing driver fatigue and concerns about serious traffic accidents when older drivers operate the steering wheel for a an extended time.

Therefore, a steer-by-wire system (SBWS) is studied as a system for driver steering assistance. SBWS is not necessary for components such as the steering shaft and gear box; it comprises small and lightweight components such as actuators and sensors; hence, it is suitable for ultra-compact EVs with small cabins. As a further advantage, by setting the reaction torque that is generated by an actuator mounted on the steering device, the driver's sensation during operation and comfort of the steering wheel can be desirably changed. In previous studies, several researchers have considered the relationship between the muscle burden of the upper limbs, the operational feeling of the steering wheel¹⁻⁴⁾, and the electromyogram (EMG) measurement and torque analysis during steering wheel operation^{5,6)}. However, the physical burden and opinion of the driver when performing the steering operation when a steer-by-wire system is installed has not been adequately studied.

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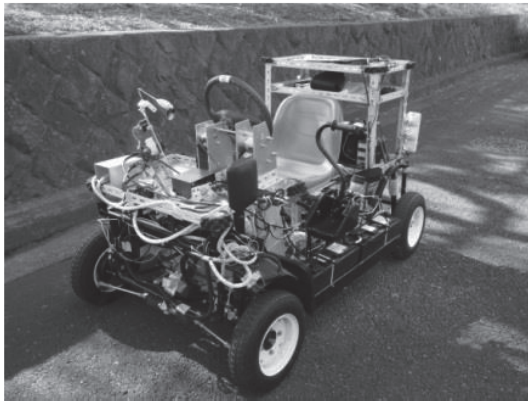


Fig. 1 Photograph of experimental vehicle.

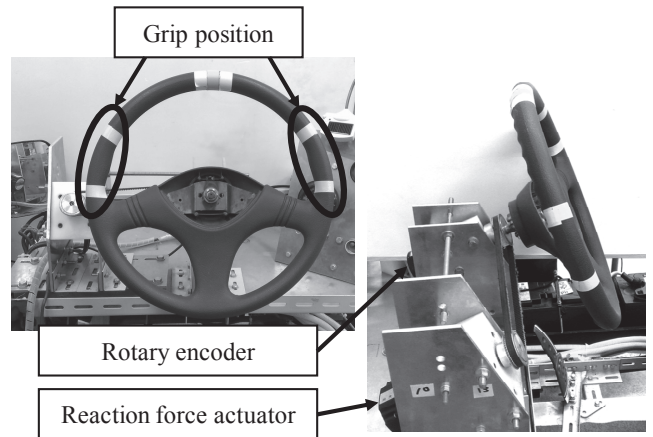


Fig. 3 Photograph of steer-by-wire system.

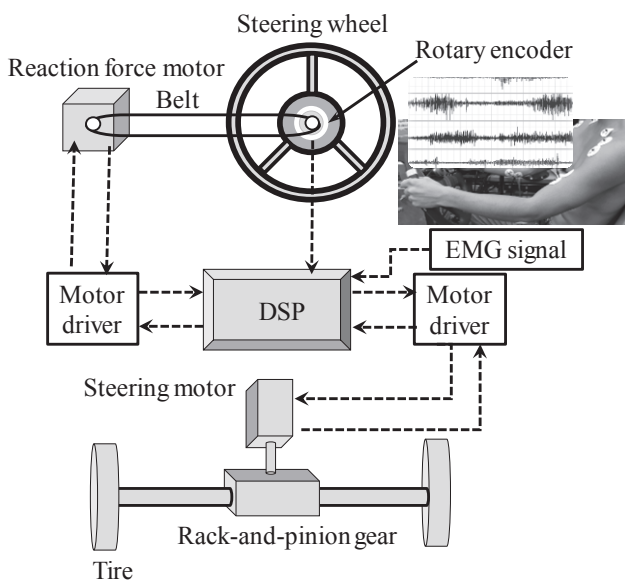


Fig. 2 Steering assist system.

The authors have studied the relationship between the steering reaction torque and muscle burden in a test environment where the driver is holding the steering wheel with SBWS mounted on the steering wheel in an ultra-compact EV⁷⁾. However, the researched range of the steering wheel's operational angle is narrow. Studies have not been conducted wherein the driver continuously operates a large angle of the steering wheel, which would require the switching operation (e.g., in a narrow alley). In this study, to develop a method for quantitatively evaluating the feeling of burden when the driver continuously operates the steering wheel, we utilize a questionnaire for the subjective evaluation of the feeling of burden during steering wheel operation and electromyogram measurement of the biological information, which can be used to evaluate the physical burden. Furthermore, the relation between the electromyogram measurement and subjective evaluation was considered.

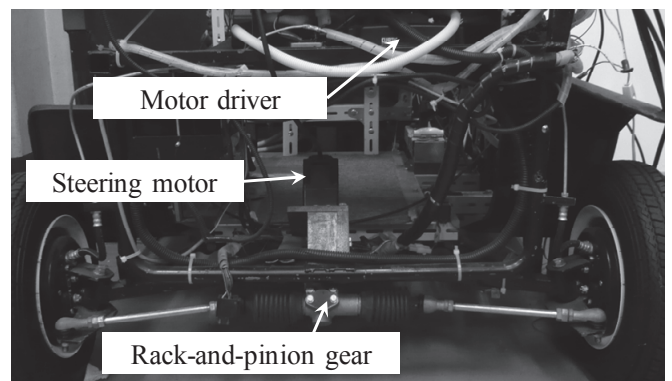


Fig. 4 Stepping motor for steering.

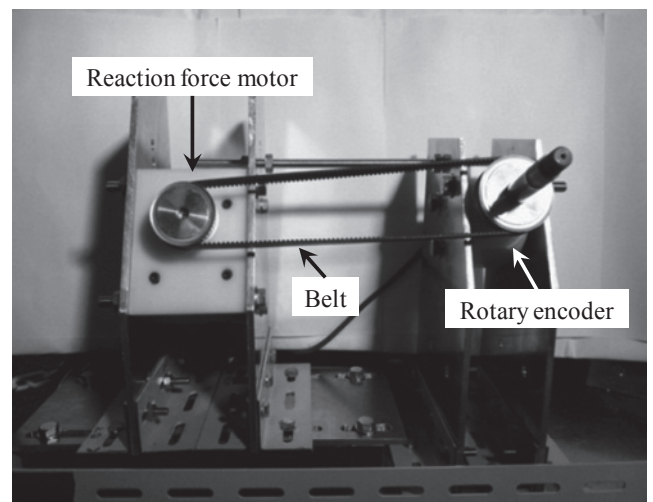


Fig. 5 Reaction-force device.

2. Ultra-compact EVs with SBWS

Figure 1 shows a photograph of the experimental ultra-compact EV equipped with SBWS in a Friendly Eco for a wheelchair made by Takeoka Motorbike Co., Ltd. The diagram of the SBWS is shown in Fig. 2. As shown in Figs. 3 and 4, the mechanical connection of the steering mechanism

Table 1 Specifications of stepping motor.

Steer-by-wire-system	CRK556APB-N10(ORIENTAL MOTOR)	
	Frame size	60 mm
	Mass	1.5 kg
	Rated current	1.4 A/Phase
	Basic step angle	0.072°
	Rated torque	5 N·m
	Maximum torque	11 N·m
Reaction-force device	BXM6200-GFS(ORIENTAL MOTOR)	
	Frame size	104 mm
	Mass	2.5 kg
	Rated output	200 W
	Basic step angle	0.072°
	Rated torque	1.3 N·m
	System maximum torque	4.5 N·m

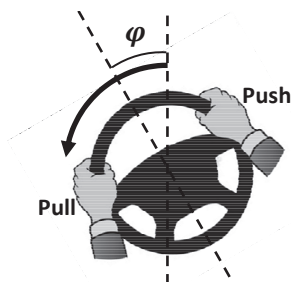


Fig. 6 Gripping position of steering wheel.

in this vehicle has been removed and the steering wheel can be operated independently. A rotary encoder for detecting the steering wheel operational angle and a brushless motor actuator for generating a reaction torque are mounted on the steering wheel, as shown in Fig. 5. The brushless motor is energized when it is confirmed by the rotary encoder that the steering wheel is being operated, and a reaction torque is generated in the steering wheel. The reaction torque is the torque generated by the brushless motor, and controlled by digital signal processor (DSP) for the operational angle of the steering wheel to return to 0°. Table 1 lists the specifications of the rotary encoder and brushless motor installed in the steering wheel. A seat from COMS, the ultra-small electric vehicle (old model) made by Toyota Auto Body, is mounted in the driver's section. The relative position between the seat, accelerator pedal, etc. is configured similar to COMS. In this study, the seat is fixed so that it does not move, and the seat position cannot be adjusted for each subject.

3. Evaluation of Burden during Steering Wheel Operation

3.1 Evaluation method

To evaluate the burden owing to steering wheel operation, we conducted a subjective evaluation using a questionnaire and an evaluation of the subjects' muscle burden using the biological information measured by a surface electromyogram. The subjective evaluation of

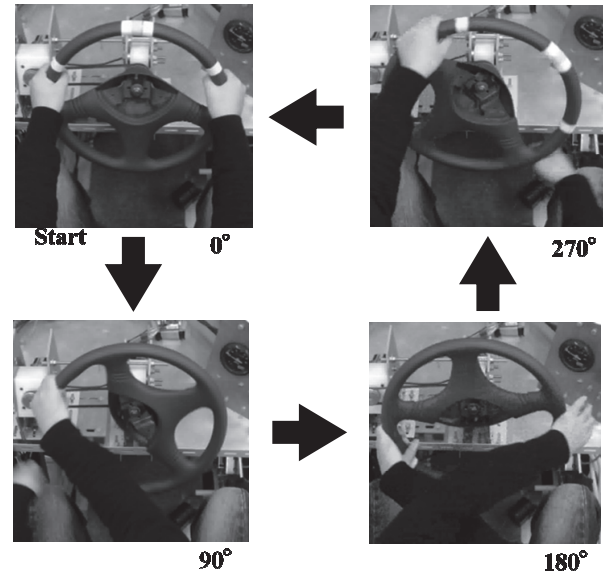


Fig. 7 Photographs of steering operation.

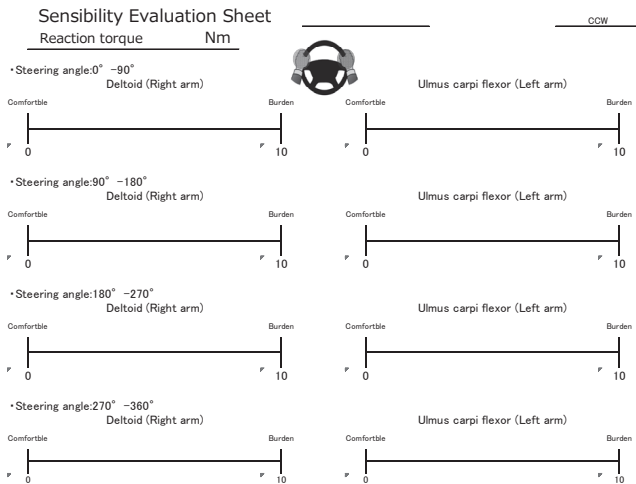
steering wheel operation was carried out using visual analog scale (VAS) for the feeling of operation burden. The evaluation of muscle burden was carried out with electromyogram measurements from electrodes attached to the subject's upper limbs during steering wheel operation. From the previous study, when the driver operates the steering wheel as shown in Fig. 6, the muscle burden of the anterior deltoid in the push-side increases the most⁷⁾. In addition, from the result of a preliminary experiment, when the subject operates the steering wheel at an angle greater than 180°, it is necessary to change over the grip (hereafter referred to as switching operation). During the switching operation, the subject operates the steering wheel with only the pulling-side hand and feels the burden in the flexor carpi ulnaris muscle. Therefore, we focused on the shoulder on the pushing-side and the wrist on the pulling-side, and evaluated the burden of the steering operation.

3.2 Subjective evaluation by questionnaire

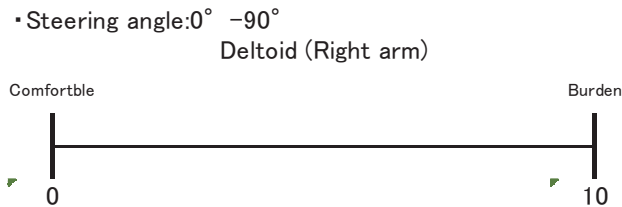
Ten healthy male students from our university participated in the experiments to operate the steering wheel in order to allow subjective evaluation of their feeling of burden. The participants were legally licensed drivers. Table 2 presents the detailed information regarding the participants. The participant sits firmly in the seat and grips the steering wheel at the position recommended by the Japan Automobile Federation (JAF), which is the so-called position at 9:15, as shown in Fig. 7. The assumed steering operation is that of turning left at an extremely low speed and instructing the subject to turn the steering wheel around once in the counterclockwise direction in 4 s. In the experiment, the metronome was set to tick 60 times per minute (once per second), such that the subject could operate the steering

Table 2 Subject information.

Subject	Age	Height [cm]	Weight [kg]	Grip strength [kg]		Driver license	Driving frequency
				Left	Right		
A	22	174.3	79.4	43.0	51.6	Licensed	Not drive
B	22	165.0	62.4	41.3	41.9	Licensed	Every day
C	22	165.0	64.3	39.6	38.2	Licensed	Holidays
D	21	171.2	75.2	38.6	47.7	Licensed	Not drive
E	22	176.4	84.6	40.3	35.4	Licensed	Not drive
F	21	174.5	89.0	45.4	41.0	Licensed	Not drive
G	22	174.2	68.8	53.2	56.2	Licensed	Every day
H	22	170.3	54.5	40.7	38.4	Licensed	Holidays
I	22	165.4	68.2	34.1	46.8	Licensed	Holidays
J	23	178.2	81.7	41.3	41.0	Licensed	Every day



(a) Overall view of the questionnaire.



(b) An example of question in the questionnaire

Fig. 8 Subjective assessment of questionnaire on the burden of steering operation.

wheel at the instructed speed. The position at which the subject's hand gripped again when the subject's arm intersected, and the subject temporarily released the steering wheel during steering was the position at 9:15.

To clarify the change in the feeling of burden owing to the difference in reaction torque applied to the steering wheel, two types of reaction torque conditions of 0.85 and 4.5 N·m were set using the brushless motor. The reaction torque is generated so that the steering wheel returns to 0°, and when it returns to 0°, the reaction torque is set to 0 N·m.

In each reaction torque condition, a subjective questionnaire was conducted every 90° for subjects who performed the steering operation experiment. The participants used a questionnaire to evaluate the burden

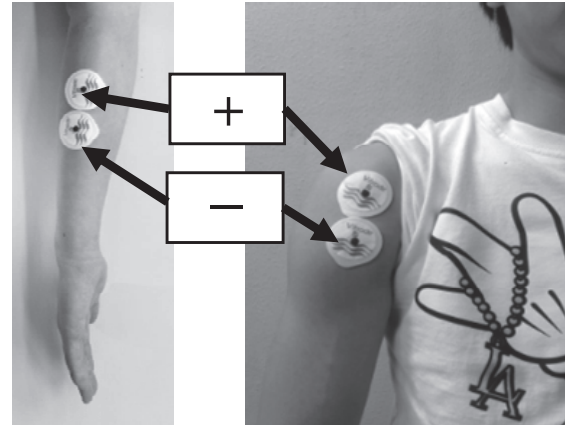


Fig. 9 Pasting positions of electrodes.

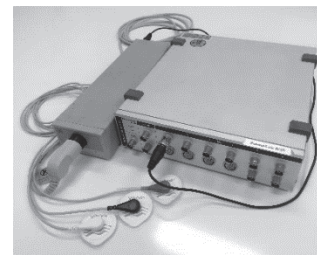


Fig. 10 Electrocardiogram measuring device.

feeling on the right shoulder including the anterior deltoid muscle of the pushing-side and the left wrist, including the ulnar carpi flexor muscle on the pulling-side. VAS was used for subjective evaluation and questions were asked as to whether each operation at every 90° felt like a burden to the subject. If the subject recorded five points or more during the 10-point evaluation, it was considered that the subject felt the burden from the operation of the steering wheel. The questionnaire used in this experiment is shown in Fig. 8.

3.3 Evaluation of burden using surface electromyogram measurements

When the subject performed the steering wheel operation experiment in the counterclockwise direction, the right anterior deltoid muscle and left flexor carpi ulnaris muscle, which are the active muscles, were measured using a surface electromyogram and the muscle burden was quantitatively evaluated. Each surface electromyogram measurement was performed by attaching electrodes to the subject's right shoulder and left wrist, as shown in Fig. 9. The electromyogram measurement is amplified (high pass 500 Hz, low pass 10 Hz) by Bio Amp FE 138 (AD Instruments) shown on the right side of Fig. 10, and measured by the A/D converter shown on the left side of Fig. 10 (Power Lab ML 825 2125, AD Instruments) at a sampling frequency of 4 kHz.

To evaluate the amplitude of the electromyogram measurement, the root mean square square (RMS) of every

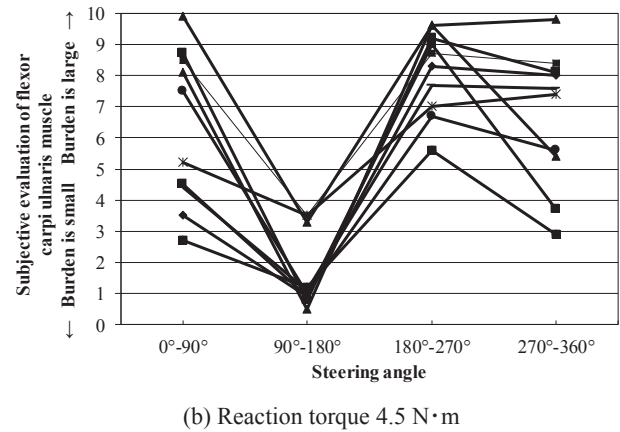
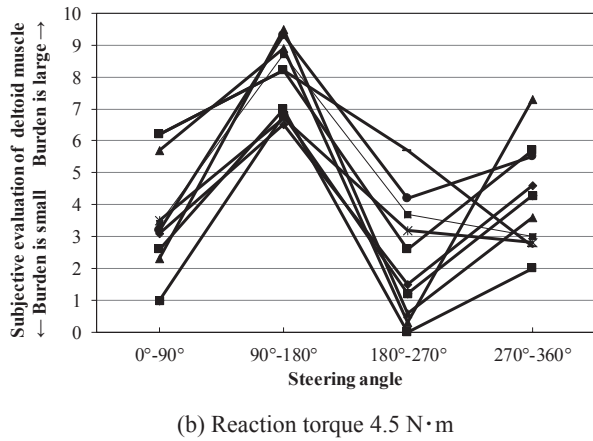
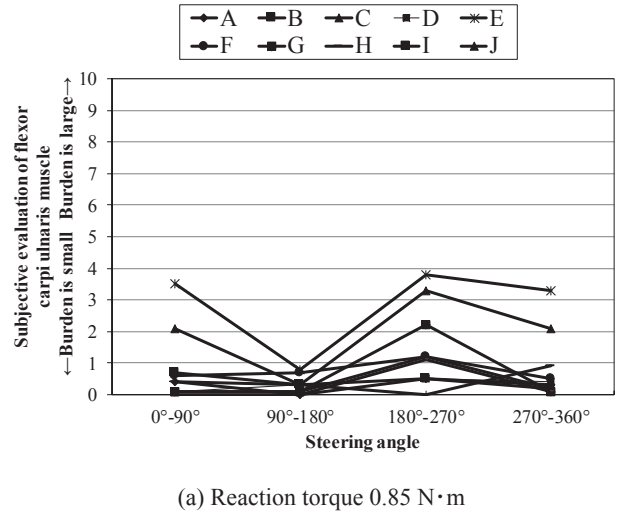
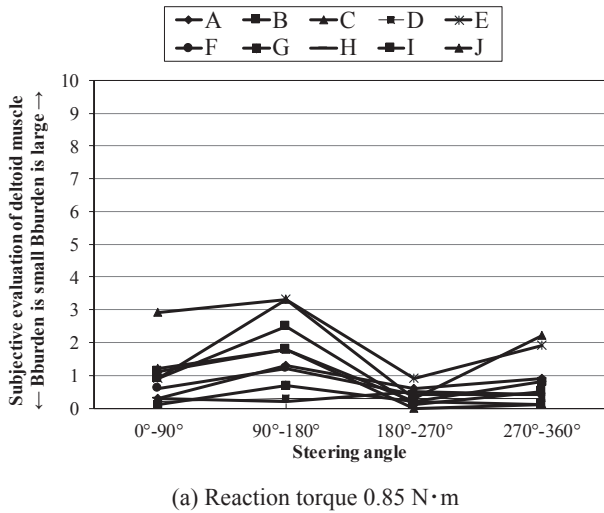


Fig. 11 Subjective evaluation result of right shoulder including anterior deltoid on pushing-side.

Fig. 12 Subjective evaluation result of left wrist including flexor carpi ulnaris muscle on pulling-side.

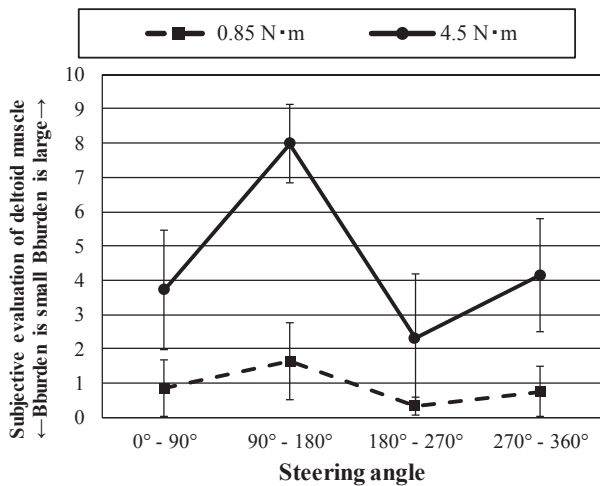
data point at 0.5 s of the time history is calculated and evaluated. Because the maximum muscular strengths that can be exerted are different for each subject, the sense of burden differs for operations with even the same load. Therefore, to normalize muscle activity during steering wheel operation with the value when the muscle force was demonstrated with maximum effort, the maximum voluntary contraction (MVC) was measured. In the measurement of the MVC of the right anterior deltoid, we instructed the participant to raise their right arm to 90° with the participant facing forward. The experimenter held the subject's shoulder and elbow so that the participant's arm did not incline more than 90°. Next, the participant was instructed to exert power with maximum effort for 10 s on the arm part, and the burden of the right anterior deltoid was measured with the electromyogram at that time. For the left flexor carpi ulnaris muscle, we measured the electromyogram in the same way as that for the anterior deltoid, with the steering gripped forcefully by the participant, and the participant facing forward at the sitting position. The %MVC, which is obtained by dividing the RMS

measured in the steering operation by the RMS of the MVC, is used for evaluation of the muscle burden.

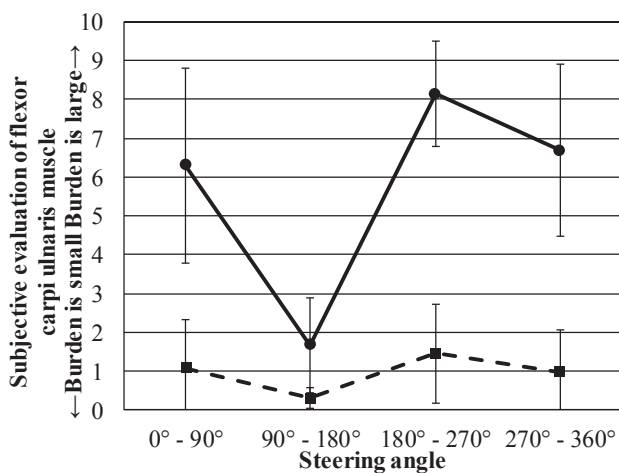
4. Experimental Results and Discussion

4.1 Experimental results of subjective evaluation

Figure 11 shows the subjective evaluation of the right shoulder including the anterior deltoid of the pushing-side of the subject after the steering experiments. Figure 11(a) shows the result when the reaction torque is 0.85 N·m and (b) shows the result when it is 4.5 N·m. In Fig. 11(a), with a reaction torque of 0.85 N·m, none of the subjects felt the burden on the shoulder area at any angle of the steering wheel. In Fig. 11(b), with a reaction torque of 4.5 N·m, all subjects felt a burden on the shoulder in the operational angle from 90° to 180°, and did not feel a burden in the range from 180° to 270°. In the range from 0° to 90° and from 270° to 360°, some subjects felt the burdens and others did not. Regardless of the reaction torque, the subjects' feeling of burden increased from 90° to 180° compared with in 0° to 90°.



(a) The anterior deltoid of the pushing-side.



(b) The flexor carpi ulnaris muscle on pulling-side

Fig. 13 Subjective evaluation result.

Further, the burden decreased from 180° to 270°, and tended to increase again from 270° to 360° in almost all cases. It is considered that the subjects were burdened by the steering operation involving only the pushing-side from 90° to 180° because the pulling-side was not holding the steering wheel for the switching operation. In addition, from 180° to 270°, it is considered that the subjects did not feel burdened because the pushing-side did not hold the steering wheel owing to the switching operation.

The results of the subjective evaluation on the left wrist including the pulling-side flexor carpi ulnaris muscle are shown in Fig. 12 in the same manner as Fig. 11. When the reaction torque was 0.85 N·m, none of the subjects felt the burden on the wrist at any angle of the steering wheel. In the case of a reaction torque of 4.5 N·m, all subjects felt a burden on the wrists in the operation from 180° to 270° and did not feel the burden in the operation from 90° to 180°. Contrary to the results of the shoulder on the pushing-side, it is considered that the steering wheel is operated only by the pushing-side from 90° to 180°, and the steering wheel is

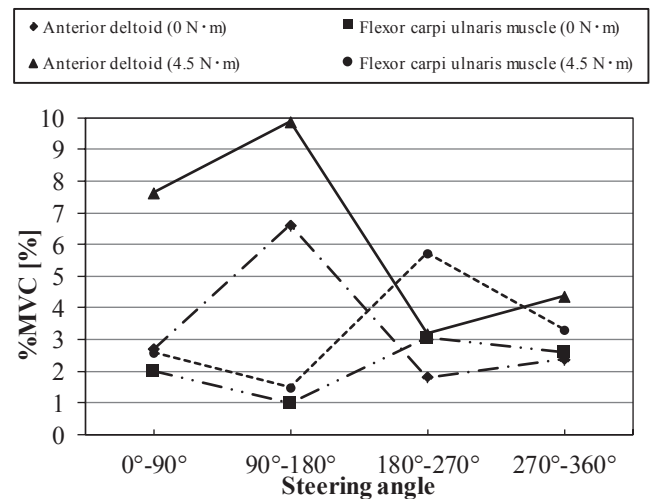


Fig. 14 Example of measured EMG of anterior deltoid and flexor carpi ulnaris muscle in each condition.

operated only by the pulling-side from 180° to 270°.

Figure 13 shows the average value and the standard deviation for the above 10 subjective evaluation results. Figure 13 (a) shows the result of the right anterior deltoid, and Fig. 13 (b) shows the result of the left flexor carpi ulnaris muscle. The steering reaction torque of 0.85 N·m and 4.5 N·m showed the same tendency in both muscles, and the tendency that the burden became large when the reaction torque increased was confirmed.

4.2 Experimental results of surface electromyogram measurements

Figure 14 shows an example of the %MVC at the right anterior deltoid on the pushing-side and the left flexor carpi ulnaris muscle on the pulling-side in the case of a reaction torque of 0.85 and 4.5 N·m. In both muscles, %MVC in the case of 4.5 N·m exceeded when the reaction torque was 0.85 N·m exceeded, and the muscle burden increased owing to the increase in the reaction torque.

In the anterior deltoid, the muscle load increases in the range of 90° to 180°, which is operating the steering wheel only with the pushing-side owing to switching operation. Thereafter, in the range from 180° to 270°, the pushing-side did not hold the steering wheel. Finally, in the range from 270° to 360°, the muscle load increased by steering with both hands.

On the other hand, because the left flexor carpi ulnaris muscle performed switching operation, the muscle burden decreased from 90° to 180° in the case that the steering wheel is not gripped. Next, because the steering wheel operation is performed only with the pulling-side in the range from 180° to 270°, the muscle burden increased. Finally, the burden increased owing to the performance of the steering wheel

operation with both hands.

4.3 Discussion

The subjective evaluation using the questionnaire in the steering wheel operation experiment and the subjects' surface electromyogram measurement results were compared. The results of the comparison indicate the tendency to increase the burden on the upper limbs holding the steering wheel on one side during switching operation and to reduce the burden when the upper limbs are not holding the steering wheel. Furthermore, from the comparison of the results in the case that the steering reaction torque is changed, the muscle burden can be reduced by decreasing the reaction torque. Also, in the subjective assessment, all the subjects evaluated that the burden was not felt at all operating angles when the reaction torque is reduced.

5. Conclusion

In this study, using SBYS, which can arbitrarily change the reaction torque applied to the steering wheel, the feeling of burden was evaluated by subjective evaluation and biological information while the driver continuously operated the steering wheel. The feel of burden in steering wheel operation was a subjective evaluation carried out using a questionnaire. The muscle burden in steering wheel operation was evaluated using the electromyogram, which measures biological information. The results show that subjects subjectively felt a heavy burden when operating the steering wheel with one hand, and this tendency was also obtained from the muscle burden. From these results, it was revealed that the switching operation is the most burdensome operation for the upper limbs of the driver. However, by reducing the steering reaction torque, it is possible to reduce the burden of subjective evaluation and muscle burden.

In future work, we will consider a system that reduces the feel of burden and muscle burden by controlling the reaction torque in the range of the steering wheel's operational angle when the driver operates the steering wheel

using one hand. Furthermore, we will perform the experiment on more subjects and examine the effectiveness. In addition, detailed investigation will be carried out on the feeling of steering operation and followability when steering reaction torque is changed, and the relationship with muscle burden will be clarified.

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