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Analysis of Human Hand Impedance Properties Depending on Driving Conditions

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***Abstract*—This paper examines the influence of driving conditions on human hand impedance properties by using an originally developed driving simulator. A set of driving tests combining driving speed and the existence of a road centerline was carried out with five subjects. The results statistically demonstrate that humans steer a vehicle with increasing hand stiffness by activating arm muscles, i.e., under some tension, on the straight load especially at a lower speed with a centerline. In addition, it was confirmed that there was a clear correlation between steering behaviors and human hand stiffness according to the driving conditions. Human impedance measurement in driving would be useful to ascertain not only steering behaviors but also driver's physical and mental conditions for driving conditions, which may be required to develop an intelligent driving support system.**

I. INTRODUCTION

A human skillfully drives an automobile by manipulating driving interfaces, such as a steering wheel and a gas pedal, according to driving conditions while adjusting the musculoskeletal system of his/her limbs. In the steering operation, for example, he/she would actively adjust arm posture and hand force to control the driving direction according to driving speed and road condition. This supposes that driver's behaviors and loads would much depend on the driving conditions as well as the vehicle performance. If such biological characteristics for a human driver in various driving conditions can be quantitatively described, it would be useful to develop a novel driving support system so that humans can drive a vehicle more comfortably and safely.

Many experimental studies have tried to develop a driver model according to driving conditions, and investigated the temporal data of eye-head movements and steering movements [1]−[4]. For an example, Kunieda et al. [1] developed an index which represent road surface condition and reported the relationship between steering behaviors and the index. No study reports, however, quantitatively analyze or clearly explain the relationship frequently observed in driving; how human drivers move their upper limbs to operate the steering wheel according to driving conditions.

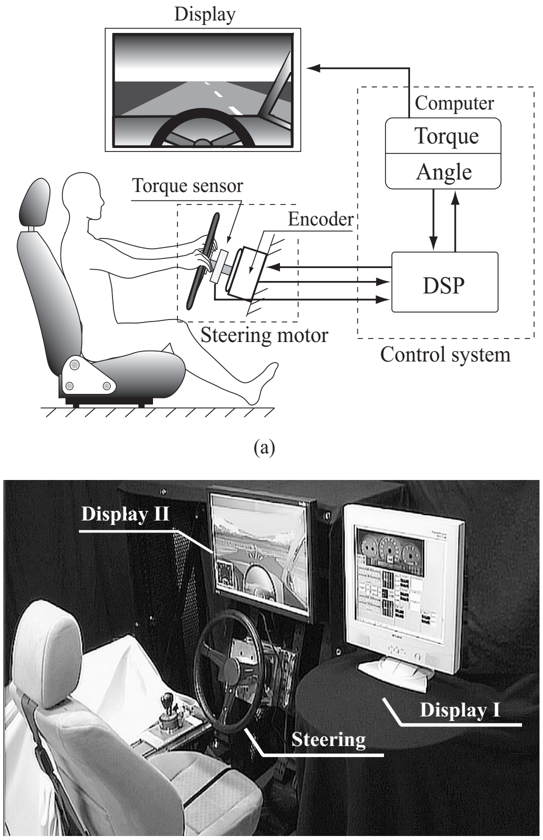
On the other hand, dynamic properties of human movements can be expressed using mechanical impedance parameters, i.e., stiffness, viscosity and inertia, and many experimental studies on human hand impedance have been reported. Mussa-Ivaldi et al. [5] pioneered the measurement of human hand impedance and examined hand stiffness in a stable hand posture, finding that stiffness strongly depends on hand posture. Dolan et al. [6] and Tsuji et al. [7]−[9] also showed that human hand viscoelasticity is widely affected by muscle activation levels during isometric contraction. These fundamental studies revealed that humans can control impedance by regulating the posture of limbs and/or muscle contraction levels during multi-joint movement.

Some studies on hand impedance characteristics during steering operations have been reported. For example, Li et al. [10] analyzed the relationship between the rotational stiffness of a steering interface and the hand stiffness through a set of theoretical and experimental analyses, and showed that an overall stiffness of the hand-steering system depends on the internal force and the muscle contraction of human arms. In our research group, human hand impedance properties during steering operation were measured by the virtual driving system [11], and the control structure inspired by human hand impedance for a steer-by-wire system has been proposed [13]. However, we have not discussed how humans change their dynamic properties according to driving conditions, such as a driving speed, a driveway orbit, and so on. This paper analyzes steering movements and human hand impedance properties in driving according to driving conditions, and discusses their relationship with quantitative indices.

This paper is organized as follows: Section II describes the developed virtual driving system, and Section III explains an estimation method of human hand impedance properties during steering operations. In Section IV, a series of measurement experiments are performed with five subjects for four different driving conditions, the lower and higher driving speeds with or without a road centerline, and statistically demonstrates the clear correlation between steering behaviors and human hand stiffness.

II. VIRTUAL DRIVING SYSTEM

Fig. 1 shows a schematic overview of the virtual driving system developed for this paper. The virtual driving system is constructed with a direct-drive-type motor (NSK, Ltd., maximum torque: 20 [Nm]), a computer for controlling the motor,



(b)

Fig. 1. A virtual driving system [11][12].

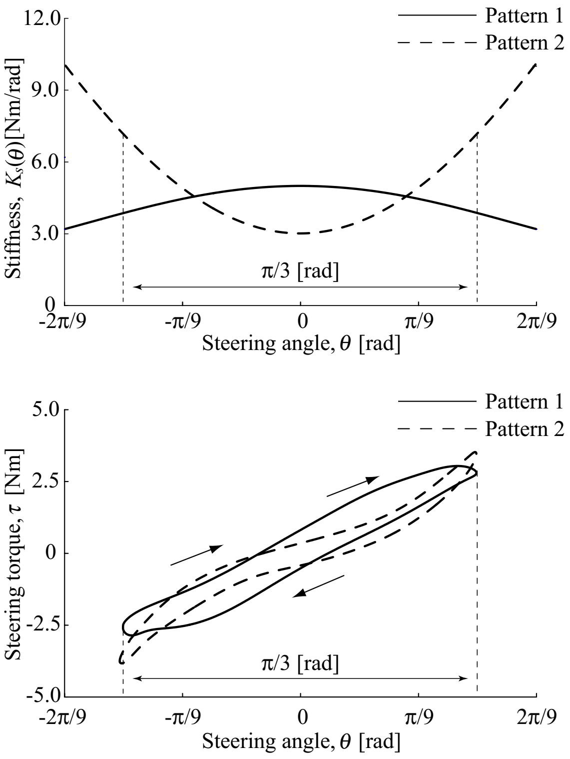


Fig. 2. Operational results for the designed viscoelastic patterns installed into the virtual driving system.

and two LCD displays to monitor steering angle and torque measured (Display I) and for the present of a driving scene created with a real-time 3-D animation software (Display II). A steering wheel (NARDI, Ltd., radius: r = 0.185 [m]) and a rotation torque sensor (SOHGOH KEISO Corp., maximum torque: 50 [Nm]) are attached to the rotating part of the motor, and the steering angle is measured by an encoder built into the motor (encoder resolution: 51,200 [pulse/r]). The motor is controlled by a DSP board (dSPACE: ds1103) that can provide stable control and high-quality data measurement at 2 [kHz] sampling-frequency.

The steering motor is controlled by a variable impedance control method to reproduce a realistic feeling of steering operations. Its dynamics can be represented as follows:

$$M_s\ddot{\theta}(t) + B_s\dot{\theta}(t) + K_s(\theta)(\theta(t) - \theta_{sc}(t)) = \tau_e(t) \qquad (1)$$

where M_s and B_s are the inertia and the viscosity of a virtual driving system, respectively; $K_s(\theta)$ is the variable stiffness as a function of the steering angle θ; θ_{sc} equilibrium for $K_s(\theta)$; and τ the steering torque generated by the operator. In this paper, the steering stiffness $K_s(\theta)$ is defined by a forth-order polynomial as

$$K_s(\theta) \quad = \quad \sum_{i=0}^{4} \alpha_i \theta^i, \qquad (2)$$

where α_i $(i = 0, 1, ..., 4)$ are the coefficients to determine the steering load.

Fig. 2 shows the stiffness patterns with respect to θ installed in the virtual driving system and the torque-to-angle profiles measured during steering operations. The steering operation range is $\mid \theta \mid \leq \pi/3$ and the equilibrium for the stiffness was set at 0 [rad]. The inertia and viscosity of the steering wheel were set at M_s = 0.03 [Nms^2/rad], B_s = 1.0 [Nms/rad]. The virtual driving system developed is able to change the steering operational feeling by regulating viscoelastic patterns. Driving tests in the next section were performed by installing Pattern 1 into the driving system.

III. MEASUREMENT METHOD OF HUMAN HAND IMPEDANCE

When the driver's hand is displaced from its equilibrium by a small disturbance in a short duration as shown in Fig. 3, dynamic characteristics of the hand around the steering rotational axis can be expressed with an impedance model [5] as

$$M_{\theta e}\ddot{\theta}(t) + B_{\theta e}\dot{\theta}(t) + K_{\theta e}(\theta(t) - \theta_c(t)) = -\tau_e(t), \qquad (3)$$

where τ_e is the steering torque generated by the operator; θ the steering angle; θ_c a virtual trajectory of hand equilibrium; $M_{\theta e}$, $B_{\theta e}$, $K_{\theta e}$ represent hand inertia, viscosity, and stiffness around the rotational axis of the steering. Assuming θ_c was

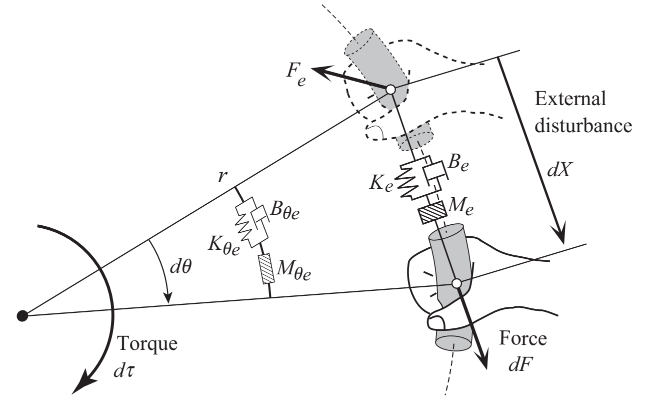


Fig. 3. Schematic description of the hand impedance measurement during steering operations.

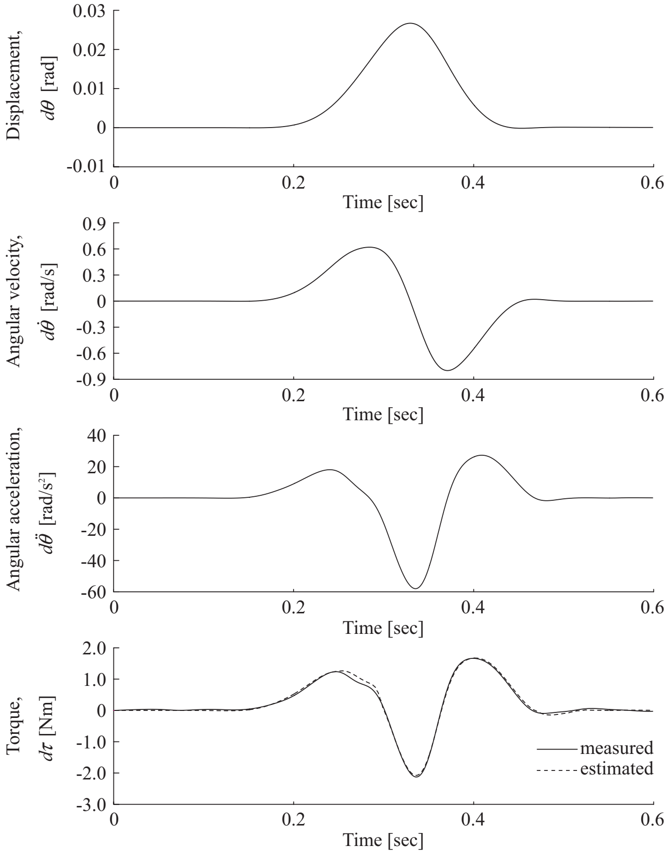


Fig. 4. An example of the measured signals for estimating mechanical impedance.

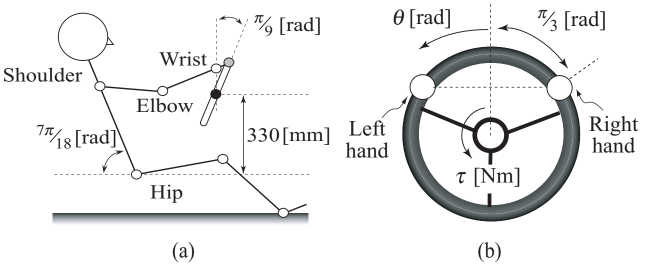


Fig. 5. Experimental condition of the virtual steering maneuvers and driving course.

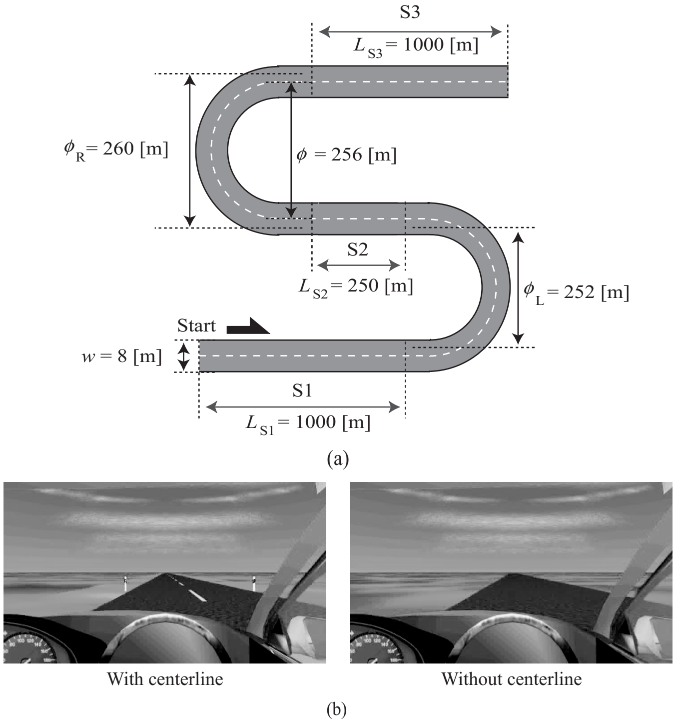


Fig. 6. Driving course and examples of the presentation screen.

constant, Eq. (3) could be rewritten as follows:

$$M_{\theta e}\ddot{\theta}(t)+B_{\theta e}\dot{\theta}(t)+K_{\theta e}(\theta(t)-\theta_c)=-\tau_e(t). \tag{4}$$

At the onset time of the external disturbance t_0, we have

$$M_{\theta e}\ddot{\theta}(t_0)+B_{\theta e}\dot{\theta}(t_0)+K_{\theta e}(\theta(t_0)-\theta_c)=-\tau_e(t_0), \tag{5}$$

and θ_c can be eliminated from Eqs. (4) and (5) as

$$M_{\theta e}d\ddot{\theta}(t)+B_{\theta e}d\dot{\theta}(t)+K_{\theta e}d\theta(t)=-d\tau(t), \tag{6}$$

where $d\theta(t)\equiv\theta(t)-\theta(t_0)$, $\tau(t)\equiv\tau_e(t)-\tau_e(t_0)$. Thus, hand impedance parameters can be estimated by fitting the measured time sequences of steering angle and torque into Eq. (6) with the least squares method.

On the other hand, a hand displacement dX corresponding to $d\theta$ can be given by

$$dX(t)\approx r d\theta(t) \tag{7}$$

and a reaction force to his hand is

$$dF(t)=\frac{1}{r}d\tau(t), \tag{8}$$

where r is the radius of steering wheel. Accordingly, dynamic characteristics of the human hand in the tangential direction of the steering wheel can be expressed as

$$M_e d\ddot{X}(t)+B_e d\dot{X}(t)+K_e dX(t)=-dF(t), \tag{9}$$

where hand impedance parameters in the tangential direction are calculated by

$$M_e=\frac{1}{r^2}M_{\theta e}, B_e=\frac{1}{r^2}B_{\theta e}, K_e=\frac{1}{r^2}K_{\theta e}. \tag{10}$$

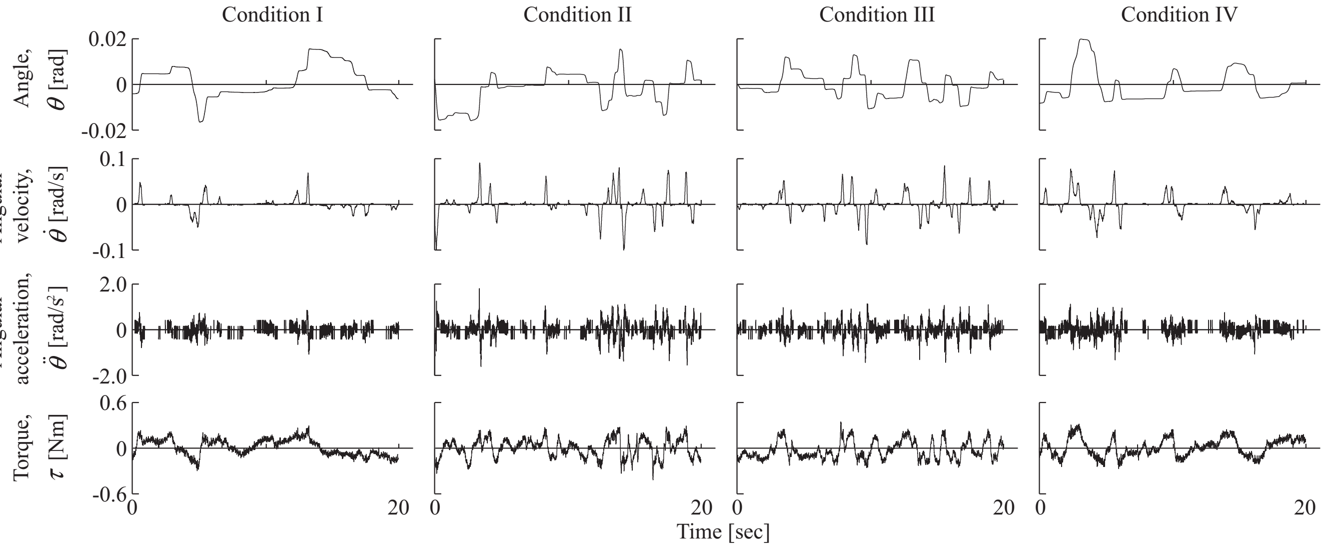


Fig. 7. Examples of measured signals on steering motion while driving on the straight line for 20 seconds.

Fig. 4 shows an example of the steering angle $d\theta$, the angular velocity $d\dot{\theta}$, the angular acceleration $d\ddot{\theta}$ and the torque $d\tau$ measured in estimating mechanical impedance properties of the known spring-mass system under M = 0.5 [kg] and K = 879 [N/m]. Mean values and standard deviation for five sets of estimated results are $M_e = 0.52 \pm 0.01$ [kg] and $K_e = 874.9 \pm 28.6$ [N/m], respectively. In the bottom figure, the solid line is the measured torque and the broken line is the calculated torque using Eq. (6) while the estimated $M_{\theta e}$, $B_{\theta e}$, and $K_{\theta e}$. The results demonstrate that the developed driving system can estimate impedance properties successfully.

IV. VIRTUAL DRIVING EXPERIMENTS

Experiments were carried out to examine the characteristics of human hand impedance during steering operation according to driving conditions. Five healthy subjects (male university students aged 22 - 24 years old) participated in these experiments.

A. Experimental condition

A human subject had a driving seat under the specified driving posture as shown in Fig. 5(a), and his shoulders were restrained to the seat back using a seatbelt. He held the steering wheel as shown in Fig. 5(b), where both hands were fixed on the steering wheel using a plastic cast to eliminate passive impedance properties of the palm.

Subjects were asked to drive on the left side of a simple S-shaped course under different driving conditions as shown in Fig. 6. In this paper, the four driving conditions are designed as:

Condition I: Driving speed 60 [km/h] without a centerline
Condition II: Driving speed 60 [km/h] with a centerline
Condition III: Driving speed 100 [km/h] without a centerline
Condition IV: Driving speed 100 [km/h] with a centerline

Hand impedance properties were measured ten times while driving on the straight lines labeled S1 and S3 for all the driving conditions (see Fig. 6(a)). External disturbances were applied to the steering wheel under $|\dot{\theta}| \leq 0.05$ [rad/s] at the interval of 5 seconds or over.

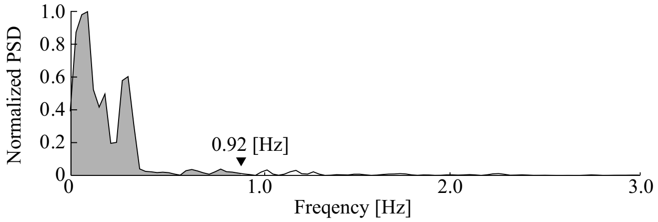
Fig. 7 shows typical time histories of steering behaviors measured for 20 seconds while driving on the straight line S1, where the steering angle θ, the angular velocity $\dot{\theta}$, the angular acceleration $\ddot{\theta}$ and the steering torque τ are plotted from the top. From the graph, it can be seen that steering behaviors change in the driving conditions provided. To quantitatively evaluate such steering behaviors depending on the conditions, two indices, time and frequency domains, are defined using the time profile of steering torque for 20 seconds.

The first index is a steering workload W as [1][14]

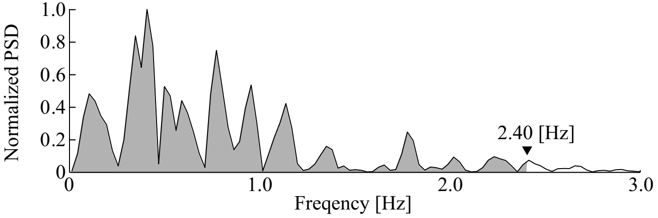
$$W = \int_0^{20} \tau(t)\dot{\theta}(t)dt. \tag{11}$$

This means that the driving load on a human becomes larger with increasing W. The second index is the upper bound frequency I of the steering torque in which the 95 % of frequency components are included. This means that a human driver actively operates the steering wheel as I increases.

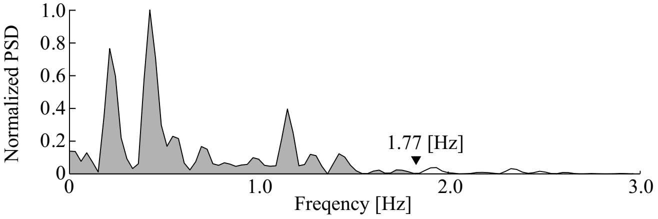
Fig. 8 shows the normalized power spectral densities (PSD) corresponding to the time histories of steering torque in Fig. 7, where PSD is calculated by the Welch method (32768-point FFT, 0% overlap, Hamming window) implemented in Matlab (Mathworks Inc.). Fig. 9 shows the evaluation results of W and I when driving on the straight lines S1 and S3, where the mean values and standard deviations for all subjects are presented. These results indicate that subjects changed the control strategy of the steering wheel depending on the combination of driving speed and road condition, but can not explain how they controlled dynamic properties of their hands in steering by the upper extremities.



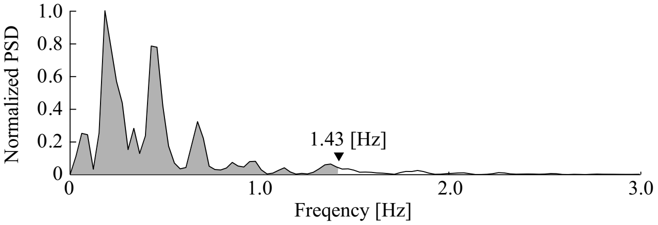
(a) Condition I



(b) Condition II



(c) Condition III



(d) Condition IV

Fig. 8. Spectral analysis of steering torque and index I at the straight line for Sub. A.

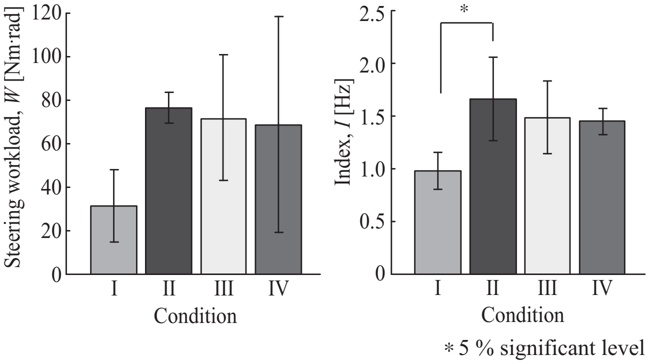


Fig. 9. Evaluation results of seering workload W and index I at the straight line for all subjects.

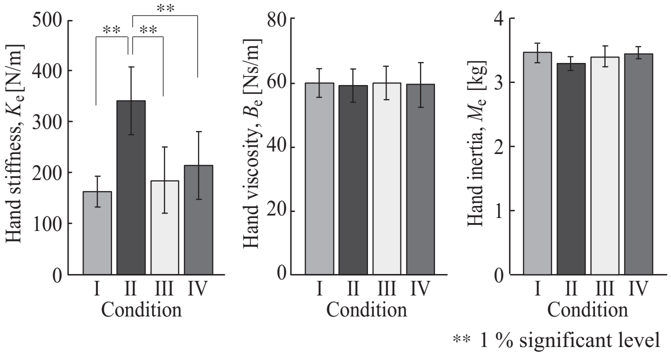


Fig. 10. Estimation results of the human hand impedance at the straight line for Sub.A.

B. Human hand impedance properties

Fig. 10 shows hand impedances measured for Sub. A, where mean values and standard deviations for ten sets are presented. Hand stiffness obviously changes depending on the driving conditions as well as steering behaviors, and were much increased in Condition II. On the other hand, hand viscosity and inertia do not make large differences. Note that these points were confirmed in the other subjects. Table I(a) shows hand impedance measured for all subjects as well. Furthermore, a multiple comparison test was carried out to statistically explain whether there exist significant differences between driving conditions, and the results are summarized in Table I(b). It can be seen that there are significant differences in hand stiffness between Conditions I and II, Conditions II and III, and lastly Conditions II and IV. This reveals that dynamic properties of a driver's hands would depend on the interaction between the driving speed and the existence of a road centerline.

It is well-known that hand stiffness increases in proportion to the muscle contraction levels [9]. Thus, the subjects made their hands stiffen when the steering torque increased by changing the muscle contraction levels of their arms. However, the experimental results in this paper have different characteristics compared to the conventional study reports in terms of viscosity. Possible reasons include the existence of an internal force between both hands and the steering wheel. It is necessary to analyze this issue as well as improve the experimental system in the future.

Finally, Fig. 11 shows the relationship between the two indices, W and I, and the hand stiffness, where the indices are positively correlated with hand stiffness ($R_{\mathrm{W}} = 0.6528$, $R_{\mathrm{I}} = 0.6229$). This supposes that dynamic properties of driver movements as well as steering behaviors can be grasped only by measuring hand stiffness in driving.

V. CONCLUSIONS

This paper investigated the changes of dynamic properties of human movement depending on conditions in virtual driving with the developed simulator. Measurement experiments with the human subjects demonstrated the influences of driving conditions into steering behaviors and human hand impedance properties in driving. Furthermore, the experiments suppose that the possibility of both steering behaviors and driver's arm conditions can be sensed only by measuring hand stiffness in driving.

TABLE I

ESTIMATION RESULTS OF HUMAN HAND STIFFNESS MEASURED ON THE STRAIGHT LINES S1 AND S3 FOR THE DIFFERENT DRIVING CONDITIONS FOR ALL SUBJECTS.

(a) Hand stiffness

Subject	Stiffness, K_e [N/m] Condition I	Condition II	Condition III	Condition IV
A	161.9 ± 30.5	338.5 ± 65.1	184.1 ± 63.4	212.5 ± 65.9
B	212.2 ± 104.2	368.4 ± 26.6	313.2 ± 137.2	378.8 ± 129.7
C	86.6 ± 31.5	248.0 ± 31.1	127.4 ± 46.6	196.4 ± 58.8
D	153.5 ± 34.2	239.4 ± 36.8	212.9 ± 51.7	191.6 ± 34.3
E	282.9 ± 43.1	438.9 ± 69.6	274.2 ± 66.5	324.2 ± 71.0

(b) Significant differences

Subject	Condition I vs II	I vs III	I vs IV	II vs III	II vs IV	III vs IV
A	**			**	**	
B	**			**	**	
C	**			**	**	**
D	**			**	**	
E	*					**

** 1 % significant level, * 5 % significant level

Future research will be directed to analyze hand impedance in driving on curved lines with adding new driving conditions. It will also be to develop a design method of a driving support system which can adjust steering dynamics depending on driving conditions as well as a reminder system based on human hand impedance properties.

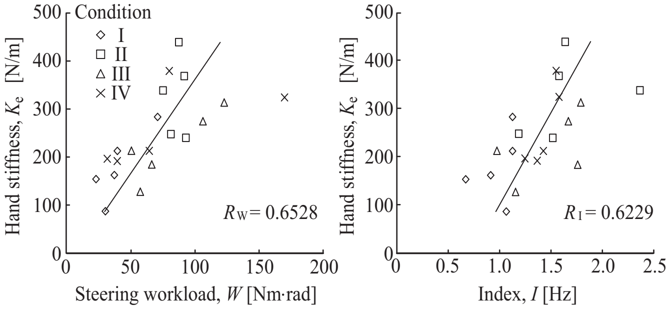


Fig. 11. Relationship between the two indices and hand stiffness for all subjects.

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