A Subjective Force Perception Model of Humans and its Application to a Steering Operation System of a Vehicle

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Abstract— **The present study clarifies the human characteristics of motion and perception, and develops a force perception model in vehicle operation. As the first step, this paper analyzes experimentally human force perception properties during steering operation, in which multiple joint motions and large postural changes of arms are necessary. The experimental results reveal the following three points: a) force perception follows the Weber-Fechner law under the constant arm posture, b) force perception changes depending on the steering wheel angle and is affected by arm weight and force perception properties, and c) the same tendency of force perception properties is observed even if the steering direction changes. Finally, a force perception model in sending a steering wheel is proposed.**

Keywords-component; Force percetion, Human model, Steering operation

I. INTRODUCTION

In automobile manufacture, the concept of *kansei* (a Japanese engineering approach by which products and services are developed and improved with consumers' psychological feelings and needs incorporated into the design domain) has taken on increased importance in recent years for making vehicle operation suit driver characteristics [1]. For example, to realize *lightness*, *linearity* and *smoothness* in handling, tuning is performed repeatedly and test driving is carried out until just the right parameters are found.

For efficient tuning of this kind, the sensory experiences of the driver must be quantified and reflected in design values in the early stages of production. Such efficient development is necessary to create simulation technology based on human sensory characteristics for this purpose. To support simulation for the nature of such sensory perception, the influence of changes in motility characteristics needs to be determined by modeling perception properties. Moreover, if the simulation of complicated operations accompanied by significant posture changes (such as those seen with steering action) can be carried out, simulation with other types of simple operation equipment will become possible. In turn, this will enable simulation to predict human sensory perception in the design phase. For this reason, simulation technology based on human sensory characteristics is necessary for each element of driving equipment to clarify human motility characteristics and the perception properties of the limbs.

Conventional research on the modeling of human motility characteristics was carried out by Mussa-Ivaldi *et al.* [2], who measured the hand displacement observed immediately after compulsive displacement and hand forces, with results clearly demonstrating that hand stiffness is dependent on arm posture. Tsuji *et al.* [3] also successfully modeled hand impedance characteristics including stiffness, viscosity and inertia. Tanaka *et al.* [4] clarified human movement impedance characteristics in relation to steering force by measuring hand impedance in steering wheel operation. In the area of leg operation [5], a manipulating force ellipsoid showing manual manipulation effort was proposed based on clarification of the characteristics of human joint torque. Hada *et al.* [6 – 8] described verification of steering wheel/pedal layout based on equivalent impedance using limb motility characteristics in consideration of contact conditions and the restrictions of a human/operation system, and carried out related implementation. Thus, the mechanism behind motility characteristics in relation to posture changes has been elucidated, and motility characteristics based on limb impedance have been modeled.

In the area of perception properties such as those of vision, Stevens *et al.* [9] proposed that the relationship between brightness (the level of sensory perception) and luminosity (the intensity of the stimulus) exhibits exponentiality, while Nagata *et al.* [10] investigated depth sensitivity in relation to distance and depth discrimination distance in relation to depth, and reported that the subjective distance of depth exhibits a saturation characteristic as proposed by Luneburg. Regarding force perception properties, research by Tsuji *et al.* [11] in robot impedance with one-dimensional straight-line motion produced three findings: a) Human impedance perception follows Weber's law; b) when only one type of impedance is replaced by three (stiffness, viscosity and inertia) and the subjects are exposed to them, their impedance perception faculty is high; and c) if the values of all three impedance types are changed and the subjects are exposed to them, their perception ability declines. In slider operation on a two-dimensional level surface, Tanaka *et al.* [12] investigated upper-limb posture with subjects wearing a hand cast. The results showed that force perception properties in hand movement followed the Weber-Fechner law, and that these properties changed with the direction of force applied to the subjects. Results obtained by Jones *et al*. [13] indicated that the thickness of each muscle affects perceptive faculty in finger, wrist and elbow joints, and that the relationship between the forces acting on an elbow and hand and the forces reproduced by the subjects is nonlinear. Thus, although force perception properties in relation to the limbs have been partially clarified under conditions of fixed posture, those associated with dual-arm movement characterized by extensive arm posture changes (such as the type seen in steering wheel operation) have not yet been elucidated.

Extensive posture changes during application of a uniform force may result in movement associated with different forces. Against such a background, this paper reports on a study conducted to clarify subjective human force perception properties in relation to hand reaction forces during steering wheel operation with extensive posture changes based on multiple joint operation, and to elucidate the relationship between these properties and motility characteristics. The modeling of force perception properties is also reported.

II. EXPERIMENT

A. Equipment

To clarify subjective force perception properties, subjects must be allowed to perceive the intended reaction force without the induction of reflexive hand movements. To achieve this, a fixed-type driving simulator was developed in the present study (Fig. 1). The equipment consisted of three pieces: (1) a direct-drive rotary motor (M-YSB, NSK, Ltd.; maximum output torque: 20 [Nm]), (2) a computer to perform motor control, and (3) a display to show steering angle values, the timing of subjects' responses and the related force perception.

The force applied to the steering wheel by the subjects was measured with a steering wheel force meter (TR60, Comprehensive Instrumentation; rated torque: 50 [Nm]) attached to the rotational part of the motor and the steering wheel (radius: r = 0.185 [m]). The steering wheel's angle of rotation was calculated using an encoder (resolution: 51,200 [pulse/rad]) built into the motor. In addition, measurement and control identical to those of steering wheel operation in an actual vehicle were realized using motor control and a DSP board (ds1103, dSPACE).

Impedance control was applied to regulate steering wheel force based on the steering wheel's angle of rotation, and the intended reaction force on the subjects' hand was generated. The dynamic characteristics of the motor are given by the following equation:

Here, $\theta^*(t)$ is the ideal steering wheel angle when the impedance characteristics of (1) are realized, M is the moment of inertia of the steering wheel, B is viscosity, K is stiffness, $\theta_v(t)$ is the hand's position of equilibrium (virtual trajectory),

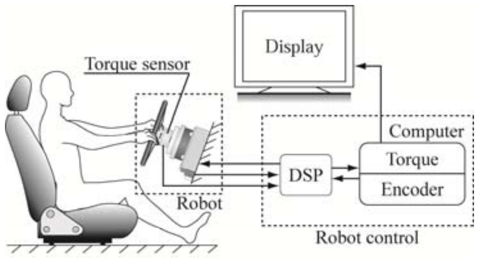


Figure 1. A driving simulator

$$M\ddot{\theta}^*(t) + B\dot{\theta}^*(t) + K(\theta^*(t) - \theta_v(t)) = \tau(t)\,. \quad (1)$$

and $\tau(t)$ is the torque applied to the steering wheel by the subject. Various steering wheel reaction forces were fed back to the subjects by adjusting these parameters in such a way that the steering wheel did not oscillate. The scale of the reaction forces applied to the subjects was adjusted using the stiffness K set for the motor. In addition, only the specified angle θ_f was used to move the position of equilibrium θ_v(t) smoothly. When reaction force was applied to the subjects, their reflex movement was controlled in line with the minimum jerk model [14].

$$\theta_v(t) = \theta(0) + \theta_f(6s^5 - 15s^4 + 10s^3) \quad , \quad (2)$$

where $\theta(0)$ is the initial angle of the steering wheel and $s = t / t_f$ is the time with t normalized by the traveling time t_f, referred to as t_f = 4 [s] and θ_f = 10 [deg.] in this experiment. To realize stable steering wheel operation, viscosity B was self-adjusted to become the damping coefficient ξ = 1.2 under a steering wheel moment of inertia of M = 0.03 [kg/m^2] in line with the stiffness K. As mentioned above, when the subjects maintained a steering wheel angle of θ (0) for the reaction force acting on the hands, the steering wheel radius was given by the following equation using 0.185 [m]:

$$F(t) = \frac{K(\theta_v(t) - \theta(0))}{0.185}\,. \quad (3)$$

To realize hand impedance control in such steering wheel operation, the target angle trajectory $\theta^*(t)$ was applied to the motor and made to follow the PID control rule of the following equation:

$$T = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \quad , \quad (4)$$

where T is the driving torque of the motor, $e(t) = \theta^*(t) - \theta(t)$ is the difference between the target angle and the present angle, and K_p, K_i and K_d are the proportional gain, the integration gain and the rate gain, respectively. In this study, the sampling frequency was set to 1 [kHz], and values of K_p = 90 [Nm/rad], K_i = 1.5 [Nm/srad] and K_d = 1 [Nms/rad] were applied.

B. Method

The subjects perceived the reaction force applied and orally indicated their perception of its scale. A measurement experiment to determine the subjects' subjective force perception properties was also conducted based on magnitude estimation, and the subjects (two college students and two working individuals aged between 22 and 45) were given adequate prior training to enable them to perform the tasks of the experiment. The posture of the subjects during the experiments is shown in Fig. 2. The average angle of the steering wheel for all four subjects was 30 [deg.], and the average torso angle was 22 [deg.]. The distance from the steering wheel to the shoulder for one subject was 580 [mm], and the distance from the hipbones to the steering wheel was 330 [mm]. The corresponding values for the other subjects were similar. In this experiment, only conditions associated with clockwise rotation of the steering wheel by 0 – 120 [deg.] were investigated. The experimental conditions were as outlined below (see Table 1).

1) Force perception properties in relation to changes in steering wheel reaction force: Testing was performed to clarify force perception properties in double-arm movement with subjects receiving reaction force from the steering wheel. This helped to elucidate how the subjects perceived different reaction forces in a state with uniform posture. Reaction force was applied by the motor based on (1) – (4). The subjects perceived this force and tried to prevent the steering wheel from rotating. With the subjects' posture maintained, steering wheel reaction force was gradually increased for t_f = 4 seconds based on (2), and for 5 more seconds with fixed steering wheel reaction force thereafter. The reaction force acting on the subjects' hands was set to $F_t = K\,\theta_f\,/0.185$. The subjects indicated the scale of the perceived reaction forces (eight comparison stimuli ranging from 5 to 40 [N]) in relation to a standard stimulus of 20 [N]. The standard stimulus was applied once first, and the comparison stimuli were then applied three times at random. The comparison stimuli were applied 5 times with each reaction force for a total of 40 times, and the steering angle $\theta(0)$ was applied with three conditions of 0, 60 and 120 [deg.].

2) Force perception properties in relation to changes in the steering wheel angle: Changes in subjects' perception with fixed reaction forces and changes in the steering wheel angle were investigated. The reaction force application method was as outlined in 2.2.1. The standard stimulus and the reaction force comparison stimulus were 20 [N]. The standard stimulus for the steering wheel angle was 0 [deg.], and the comparison stimuli were 0, 30, 60, 90 and 120 [deg.].The comparison stimuli were applied at random a total of 25 times (5 for each steering wheel angle). The other experiment conditions were as described in *Method 1)* .

III. RESULT AND DISCUSSION

A. Force perception properties in relation to changes in steering wheel reaction force

The relationship between human perception of changes in steering wheel reaction force and the given physical quantities is illustrated in Fig. 4. The figures indicate the results for one subject, the average for all four subjects and the standard deviation (SD), with (a), (b) and (c) indicating outcomes for steering angles of 0, 60 and 120 [deg.], respectively. The horizontal axis shows the force F_t, the vertical axis shows the force F_p as perceived by the subject, and the solid lines show values obtained from the following equation using the least-squares method:

$$F_p = a\log(F_t) + b \quad . \tag{6}$$

All figures show p-values computed from (6) with the coefficients a and b, the coefficient of determination r^2 and the results of one-sided testing. It can be seen that for all conditions, r^2 is 0.88 or more, and the p-value is 0.047 or less. The experimental results are reproduced by (6) for all conditions.

TABLE I. EXPERIMENTAL CONDITION

	2.2.1	2.2.2
Standard: comparing angle of rotation	Same angles	Different angles
Reaction force	Diffrent forces	Same forces
State of reactive force	Static	Static

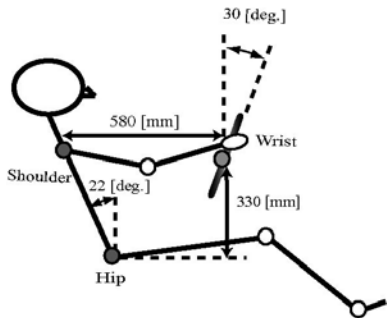


Figure 2. Experimental condition

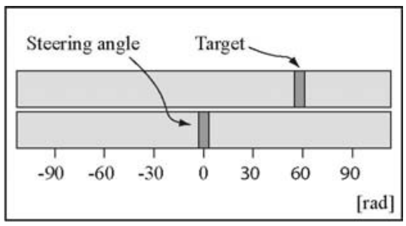
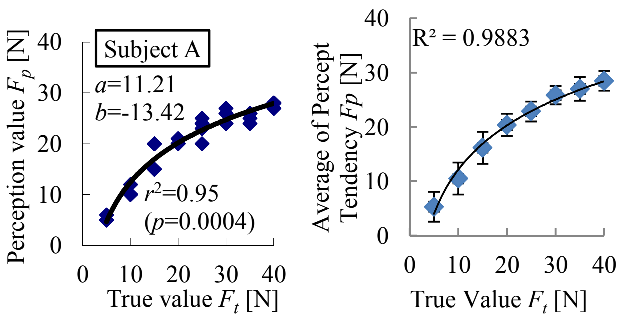


Figure 3. Target position for the steering angle

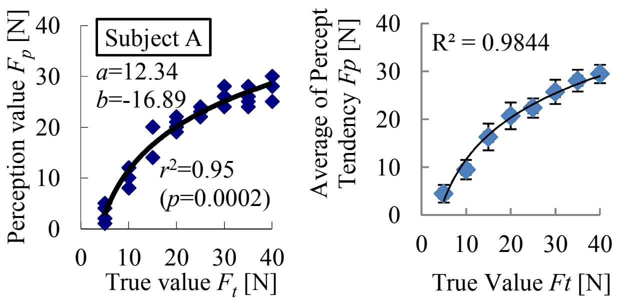
These results indicate that the perceived force follows the form of a proportional logarithm with true reaction force (i.e., perception is blunt with large reaction forces). This indicates a general correspondence to the Weber-Fechner law and a tendency similar to that of force perception properties observed in right-hand operation [11]. This tendency is the same with greater steering wheel angles. It was clear that force perception properties do not change significantly as long as the posture with the standard stimulus and the comparison stimuli remains the same.

B. Force perception properties in relation to changes in the steering wheel angle

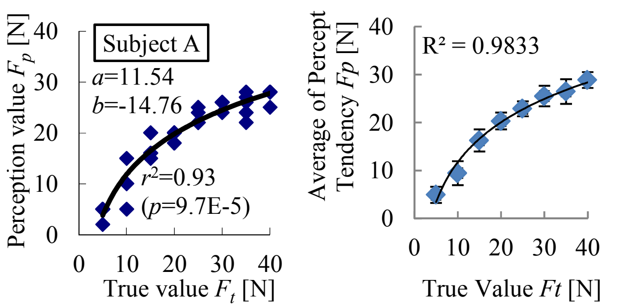
The experimental results outlined in *Method 2)* relating to the influence of steering wheel angle changes on human force



(a) $\theta(0) = 0$ [deg.]



(b) $\theta(0) = 60$ [deg.]



(c) $\theta(0) = 120$ [deg.]

Figure 4. Relationship between true and perceived forces for three different steering angle $\theta(0)$

perception properties are shown in Fig. 5. The figures indicate the results for one subject, the average for all four subjects and the standard deviation (SD). The perceived force F_p of the steering wheel angle $\theta(0)$ is shown on the horizontal axis, and the subject's perception is shown on the vertical axis. The solid lines show values obtained from the following equation using the least-squares method:

$$F_p = c(F_t) + d\ . \tag{7}$$

In addition, all figures show the coefficients c and d, the coefficient of determination r^2 and the p-value computed via one-sided testing. To suppress the influence of variations in replies from subjects, the two points farthest from the average were excluded and the results for three points were plotted with ■, ▲ and × marks from the results of five trials with each condition. Although variations among subjects were observed, a tendency for the perception of small forces was seen for all subjects when the steering wheel angle was large. This was presumably because of the influence of the end-point force of arm weight in relation to tangential adjustment of the steering wheel, changes in the exertion efficiency of force due to posture changes, variations in muscular state and other influences.

Then, the influence of the end-point of arm weight was investigated via the following procedures: (1) Subjects gripped the steering wheel with reduced strength; (2) the torque of the steering wheel was measured with different steering wheel angles; and (3) based on the end-point force of arm weight, the hand force added along the tangential direction of the steering wheel was computed. Figure 6 shows the measurement results for one subject, the average for all four subjects and the standard deviation (SD). The dashed line shows the hand force of the left arm, the alternate long/short dashed line shows the hand force of the right arm, and the solid line shows the hand force of both arms. These results show that hand force in relation to the end-point force of arm weight changes with posture.

In the experiment outlined in *Method 2)*, the reaction force applied to the subjects was in the counterclockwise direction of the steering wheel, meaning that the subjects needed to generate hand force in the clockwise direction. As such hand force cooperates with the end-point force of arm weight, it was unnecessary for the subjects to generate hand force from the end-point force of arm weight, and little hand force was generated. From this, it can be surmised that the scale of force perception decreased. To verify this, the reaction force applied to the subjects was reversed and force perception was investigated. In this way, with reaction force applied in the same direction as end-point force, checking was performed to determine whether the amount of force perception was as shown in Fig. 5 with a reverse tendency. In this case, the subjects needed to apply reverse force with the direction of the hand force based on end-point force. In this way, the subjects had to generate a greater force to maintain the position of the steering wheel. The outcomes are given in Fig. 6, which shows the results for one subject, the average for all four subjects and the standard deviation (SD). The perceived force F_p of the steering wheel angle $\theta(0)$ is shown on the horizontal axis, and the subject's perception is shown on the vertical axis. The solid lines show values for steering wheel angles from 0 to 60 [deg.] as determined using the least-squares method based on (7). In addition, all figures show the coefficients c and d, the coefficient of determination r^2 and the p-value computed via one-sided testing. As expected, a tendency for the perception of larger forces and for a reversal of the results shown in Fig. 5 was observed with all subjects as the steering angle increased from 0 to 60 [deg.] .

However, a tendency for force perception to decrease with values of 90 – 120 [deg.] was also observed with all subjects. If the influence and the muscle contraction efficiency associated with the force accompanying posture changes increase [13], the greater rigidity of the arm moving upward [15] can be suggested as a cause.

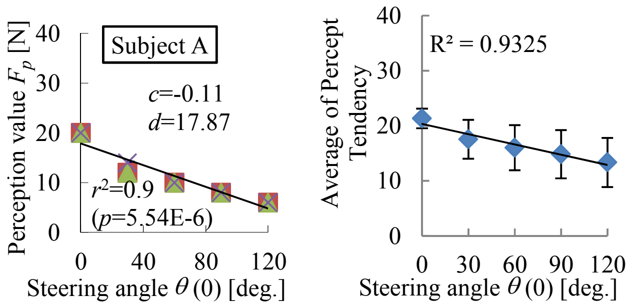


Figure 5. Change of perceived forces depending on the steering angle $\theta(0)$

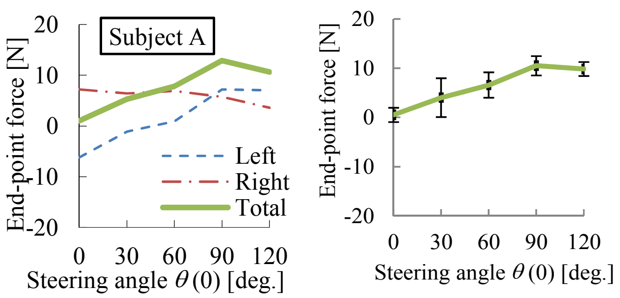


Figure 6. End-point forces caused by arm weight depending on the steering angle

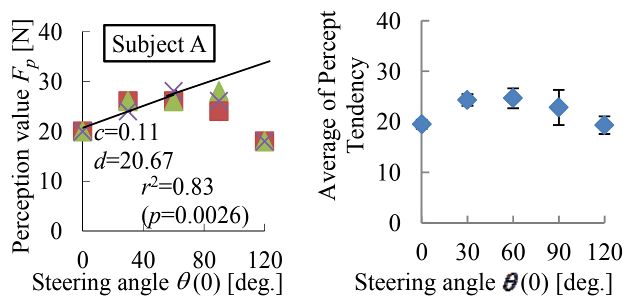


Figure 7. Change of perceived forces depending on the rotating direction

Influence on the perception of reaction force from the steering wheel direction was clarified with steering wheel movement in the opposite direction (i.e., counterclockwise rather than clockwise). The outcomes are given in Fig. 8, which shows the results for one subject with the perception tendency for downward right shoulder movement as in Fig. 5. This clarifies that there was little influence in the perception of reaction force in the steering wheel direction.

IV. Modeling

A subjective force perception model was examined based on the experimental results shown in the previous section. In addition to perception properties based on the conventional Weber-Fechner law, the proposed model incorporated the newly clarified influence of perception properties based on the steering wheel angle. The following (8) was derived from the result of two conditions (*III.A* , *III.B*):

$$F_p = \{a\log(F_t)+b\} - \{a\log(F_{nom})+b\} + \{c\theta + d\}$$
$$(\Phi_\tau\text{: } 5 \sim 40\ [\text{N}]) \qquad (8)$$

The first term on the right-hand side of this equation corresponds to (6), and expresses the subjective hand force component that changes with the scale of the hand reaction force applied. The second term on the right is to set the first part to 0 at the time of application of the standard hand force F_{nom} (F_{nom} = 20 [N] here). The third term on the right corresponds to (7), and expresses the component of change with the steering wheel angle. Then, the following standardized and universal model (9) is derived from (8):

$$F_p = a\log(\frac{F_t}{F_{nom}}) + c\theta + d \quad (\Phi_\tau\text{: } 5 \sim 40\ [\text{N}]), \quad (9)$$

Where a is the average value of the results obtained for all steering wheel angles (0, 60 and 120 [deg.]) with all four subjects as described in *III.A*, c and d are the average values of the results for the four subjects as described in *III.B* (with anticlockwise reaction force generated) , and F_p was calculated for values from 5 to 40 [N]. To clarify the accuracy of this

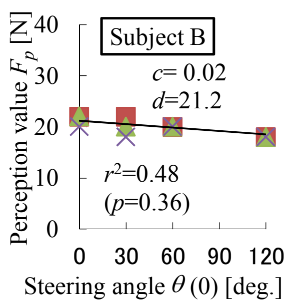


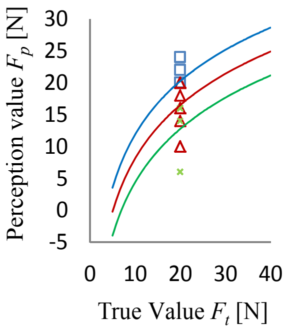
Figure 8. Change of perceived forces depending on the steering angle (the left rotation direction)

model, Fig. 9 shows the actual measurement results of perception obtained in *III.B* and the estimated results based on (9). The force F_t is shown on the horizontal axis, the force F_p as perceived by the subjects is shown on the vertical axis, and the solid line shows the results from (9) as determined using the least-squares method. In Fig. 9 (a), 0 [deg.] is shown by □, 60 [deg.] by Δ, and 120 [deg.] by × with actual measurements plotted. Fig. 9 (b), (c), and (d) show the average and SD values of the perception results for the four subjects depending on the steering wheel angles. These figures indicate that the estimated values based on (9) overlapped with the average of actual measurements. This is because (9) incorporates the influence of the steering wheel angle unlike (6), which incorporates only reaction force perception properties. Further perception measurement is needed to determine accuracy with each steering wheel angle and values other than a reaction force of 20 [N]. This is considered as a subject for future study.

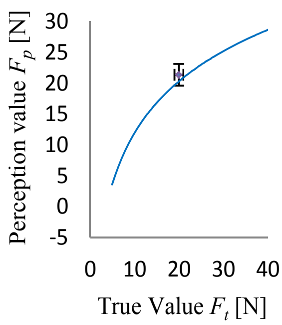
V. CONCLUSION

In this study, human subjective force perception was measured with multiple joint movements in double-arm action for steering wheel operation accompanied by complex motion with significant posture changes. The results showed that force perception a) followed the Weber-Fechner law with regular posture, and b) varied with posture changes associated with the steering wheel angle and the influence of the end-point force of arm weight. Influence in relation to the steering wheel direction was observed. Finally, force perception properties associated with steering wheel movement were modeled.

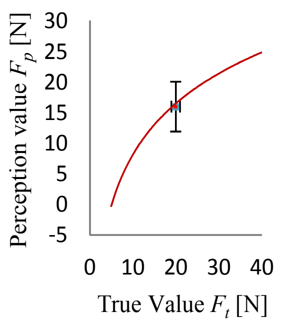
In future studies, work will be performed to further verify the accuracy of the model described in this paper. Operation performance in relation to changes in the reaction force characteristics of the steering wheel and human force perception will also be evaluated.



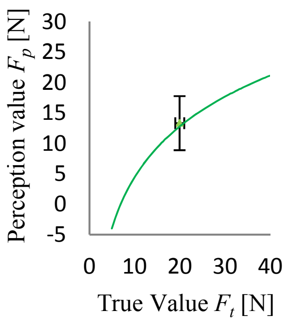
(a) estimated result of the (9)



(b) $\theta(0) = 0$ [deg.]



(c) $\theta(0) = 60$ [deg.]



(d) $\theta(0) = 120$ [deg.]

Figure 9. Estimate result of the (9) and the actual measurement

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