Development of the Perceived Force Prediction Method and Application for Force-Feedback Technology based on Muscle Activity

(筋肉の活動度に基づく力感覚量推定法の提案とアシスト技術への応用)

by

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background and Purpose

Human motion control is realized by coordinating information which perceived by various senses such as visual sense and tactile sense. In addition, because the gravity exist on the earth, the sense of force/heaviness is one of the important elements in the motion control. Then, how do we perceive force/heaviness? It is perceived by muscles which is organs that generate force. The ability to sense motion of a joint or limb including the sense of force/heaviness is called kinesthesia, and it is perceived by the proprioceptor which exists in the muscle and skin. As shown in Fig. 1.1, the sensory area including force and weight, is affected by both signals sent peripherally and signals generated peripherally as a result of motor activity [1].

However, the human's sense is not a device to measure physically, but is made as a device to infer the outside. Therefore, human perceptual characteristics are known to be nonlinear; that is, there are differences between actual force and perceived force [11,12]. Perceived force/heaviness has traditionally been believed to depend on physical (e.g., colors, and surface condition of lifted objects) and/or psychological (e.g., fatigue of muscle) factors, as reported by Jones et al. [13]. Fig. 1.2 shows the example of the factors. De Camp [2] demonstrated that perceived weight is affected by object's color,

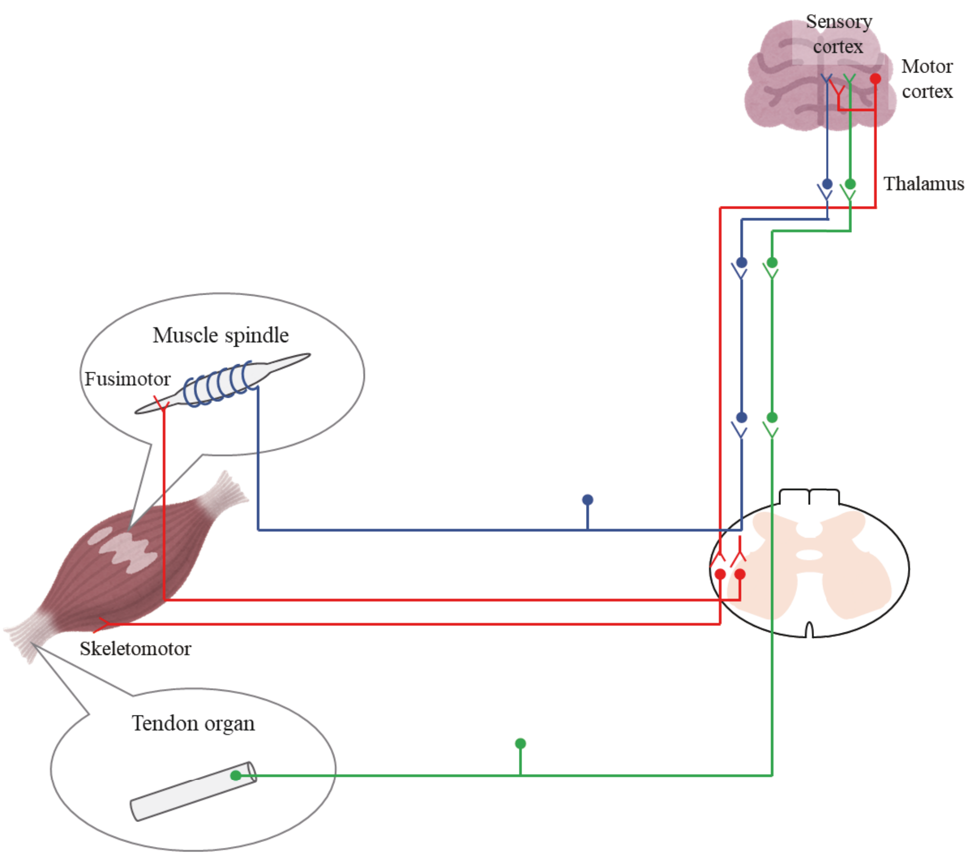


Fig. 1.1: Sketch diagram of postulated pathways taken by activity arising in sensory receptors and in motor cortex concerned with generation of the senses of effort, force and heaviness [1].

reporting that darker-colored objects are perceived to weigh less than lighter-colored objects. Additionally, it is well known that fatigue affects sense of force/heaviness [5–7].

In daily life, an automobile is an example of a system involving a human-machine interaction based on sense of force. Sense of force is thought to be important when driving an automobile, and perceived force changes while driving. Newberry et al. [14] found that the sensation of the force exerted by the steering wheel increases with a power of 1.39, according to Stevens' power law [15] for steering wheel reaction forces ranging from 5.25 - 21 N and power of 0.93 for a steering wheel angles ranging from 4

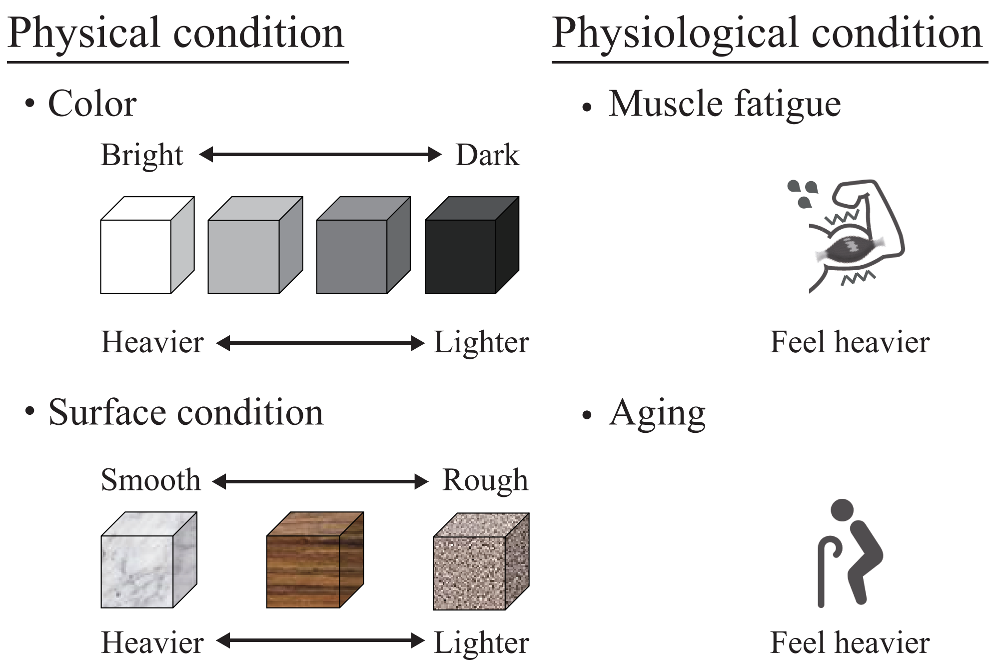


Fig. 1.2: The perception of force/heaviness affect the physical and physiological factors [2–7].

- 16°. These parameters of power represent the ratio of the intensity of the subject's perceived exertion of force to the actual exertion. Takemura et al. [16] investigated the perceived force characteristics for a wide range of steering angles using psychophysical experiments and reported that the characteristics followed Weber-Fechner ' s law [17]. This law states that perceptual intensity is proportional to the logarithm of the stimulus. It has also been reported that muscle activity changes according to the steering posture of the automobile, which changes sense of force [18].

This dissertation addresses the following topics:

- **Investigation of force perceptual bias in unimanual steering** The muscle activity is changed due to the posture changing, and then this change affect the perceived force. This effect is called force perceptual bias. In the experiment, this perceptual bias is measured from psychophysical experiment. In addition, the relationship between muscle activity and perceptual bias is investigated by using 3D musculoskeletal model simulation during the experiment. Finally, the simulation of the psychophysical experiment is conducted by using the perceived force prediction model.

- **Prediction of Perceived Force from Muscle Activity during Steering Wheel Operation** Prediction of perceived steering wheel operation force by muscle activity is described. Previous study has been reported that the force perception characteristics of steering force is following Weber Fechner's law. This law states that perceptual intensity is proportional to the logarithm of the stimulus. First, the muscle activity is estimated by using 3D musculoskeletal model simulation during steering wheel operation, then the perceived force prediction model is developed based on Weber Fechner's law by using relationship between muscle activity and the perceived force. Finally, the perceived force of commercially available vehicle is estimated by using the model to verify the accuracy of the model.

- **Development the haptic suit by using artificial muscle to change the subjective weight/force perception** The muscle activity affects the human's sense of force/weight. Take advantage of this knowledge, the haptic suit which changes the human's force/weight sense by assisting and resisting the force is developed. The McKibben rubber artificial muscle is attached in this suit to make the force. In the experiment, the subjective perceived force is measured by using this suit to verify the performance of the suit.

1.2 Related Work

1.2.1 Force Perceptual Bias

To investigate perceptual bias, which creates a perception that is larger or smaller than the actual scale, psychophysical experiments have been conducted. Using a psychophysical experiment, van Polanen et al. [19] revealed that bias that overestimates actual weight occurs when there is a visual delay in lifting an object in a virtual reality environment. They investigated the multisensory effect (lifting an object with a visual delay) on the perceived weight [19]. Flanagan et al. [3] found that when lifting an object using a precision grip with the distal pads of the thumb and index finger, bias changed depending on the object's surface texture. When the surface texture of the lifted object is smooth, the perceived weight increase. Additionally, Sakajiri et al. [8] report that perceptual bias is generated by a difference in the reaction force direction while steering an automobile. Flanagan et al. and Sakajiri et al. report that regarding sense of effort, bias can be affected by whether muscle force functionally acts on movement. This indicates that muscle is one key factor of force/weight perception.

This dissertation outlines the investigation of the postural dependent force perceptual bias in uni-manual steering. In the experiment, the force perceptual bias was investigated using the stair case method, and the experimental result is statistically analyzed. And, the postural data is measured in experiment, then muscle activity is estimated by using 3D musculoskeltal model simulation with experimental data.

1.2.2 Relationship between Sense of Effort and Muscle Activity

It has previously been reported that sense of effort and perception of force/heaviness are linked because during muscle fatigue or paralysis, we perceive both a sense of increased force/heaviness and an increase in effort [1,20–22]. Sense of effort is a motor command generated by the central nervous system, and it refers to a signal sent from the brain to a peripheral system. The larger the motor command, the more power a human can exert, and the size of the motor command relates to the sense of effort size. Cafarelli et al. [23] used the intensity of muscle activity as a sense of effort to investigate the relationship between muscle length and sense of force. Moreover, Morree et al. [24] provide neurophysiological evidence that movement-related cortical potential amplitude is correlated with sense of effort. Thus, previous studies have indicated that sense of force/heaviness can be evaluated based on muscle activity, which can be interpreted as sense of effort. The findings described above suggest that bias could potentially be caused by changes in muscle activity.

This dissertation proposes a model for predicting the perceived force during steering operation from muscle activity. This model is based on the Weber-Fechner law. This law states that perceptual intensity is proportional to the logarithm of the stimulus. In the model, the perceptual rate can be calculated directly from the intensity of muscle activity. The muscle activity is estimated by using 3D musculoskeletal model simulation.

1.2.3 Haptic Device

Virtual reality (VR) is widely used in various fields such as sports, media, and education. Although it is possible to create the environment including the realistic sensation even only by VR itself, in addition, haptic device which is linked with VR give us higher sensation. In particular, the development of force feedback devices is widely developed. The force feedback device is roughly divided into two types, a hand-held type using a controller type device and a wearable type which is directly attached to the hand or suit. Handheld type can present the force sense mainly to hands and fingertips. For example, Shifty [25], which change the sense of weight by using the inertia of the controller, Drag: on [26], which present a sense of force by using air resistance, and CLAWS [27], which present a sense of hardness, texture, and force by using small servomotor. In the wearable type, it is possible to present the larger force mainly by attaching the actuator directly to the body. For example, Wolverine [28], which presents the shape and hardness of an object by using breaking mechanism of slider, Synesthesia suit [29], which is a tactile presentation suit by using vibrator, and Muscleblazer [30], which can present force directly by using the artificial muscle. The development of the force feedback device which presents the high quality haptic sensation by various approaches is tried.

This dissertation outlines the development of haptic suits that assist the sense of force/weight. The suit has three artificial muscles attached to the front and back of the elbow joint, and can assist and resist the movement of the joint. The force perception is changed due to affect the intensity of muscle activity by using assist and resist force from artificial muscle.

1.3 Content Outline

The thesis is organized as follows:

In Chapter 2, prediction of perceived steering wheel operation force by muscle activity is described. Previous study has been reported that the force perception characteristics of steering force is following Weber Fechner's law. This law states that perceptual intensity is proportional to the logarithm of the stimulus. First, the muscle activity is estimated by using 3D musculoskeletal model simulation during steering wheel operation, then the perceived force prediction model is developed based on Weber Fechner's law by using relationship between muscle activity and the perceived force.

Finally, the perceived force of commercially available vehicle is estimated by using the model to verify the accuracy of the model. The results show that the validity of the model is demonstrated.

In Chapter 3, the effect of postural dependency for the perceived force is described. From the result of Chapter 2, it was indicated that the muscle activity is changed due to the posture changing, and then this change affect the perceived force. This effect is called force perceptual bias. In the experiment, this perceptual bias is measured from psychophysical experiment. In addition, the relationship between muscle activity and perceptual bias is investigated by using 3D musculoskeletal model simulation during the experiment. Finally, the simulation of the psychophysical experiment is conducted by using the perceived force prediction model. The results of the prediction indicated that it is possible to predict perceptual bias with relatively high accuracy using muscle activity.

In Chapter 4, the development of haptic suits that assist the sense of force/weight is described. The knowledge of muscle activity affects the human's sense of force/weight is obtained in Chapter 2 and Chapter 3. Take advantage of these results, the haptic suit which changes the human's force/weight sense by assisting and resisting the force is developed. The McKibben rubber artificial muscle is attached in this suit to make the force. In the experiment, the subjective perceived force is measured by using this suit to verify the performance of the suit. The result shows that suit is able to change the perceived force.

Finally, Chapter 5 concludes the dissertation and outlines related challenges and future work.

Chapter 2

Force Perceptual Bias in Unimanual Steering

2.1 Introduction

The rest of the Chapter is organized as follows. Section 3.2 describes the procedure of psychophysical experiment and muscle activity estimation. Section 3.3 explains the results of Section 3.2 In Section 3.4, the author discuss about the each result of experiment and estimation respectively. Finally, Section 3.5 presents our conclusions and future work.

2.2 Experiments

2.2.1 Measurement Force Perceptual Bias

Participants

The participants included nine healthy, right-handed subjects (nine males; mean [SD]: 21.8 [1.6] years old; 1.75 [0.06] m; 69.5 [6.7] kg). Of the nine participants, eight have official driver's licenses, and two drove on a regular basis. All participants gave written informed consent before participating in the study. Participants were paid for their time. The experimental procedures were previously approved by the local research ethics committee (Nagoya Institute of Technology).

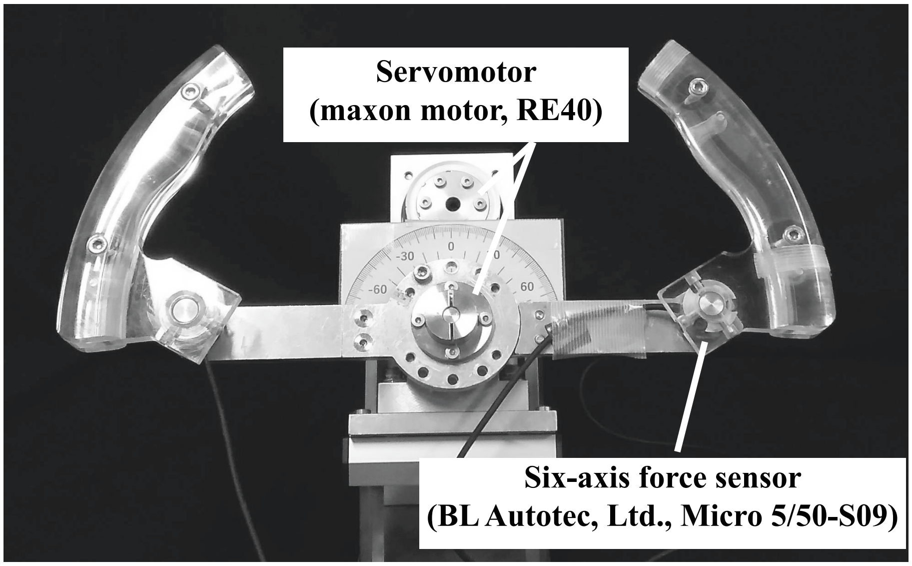
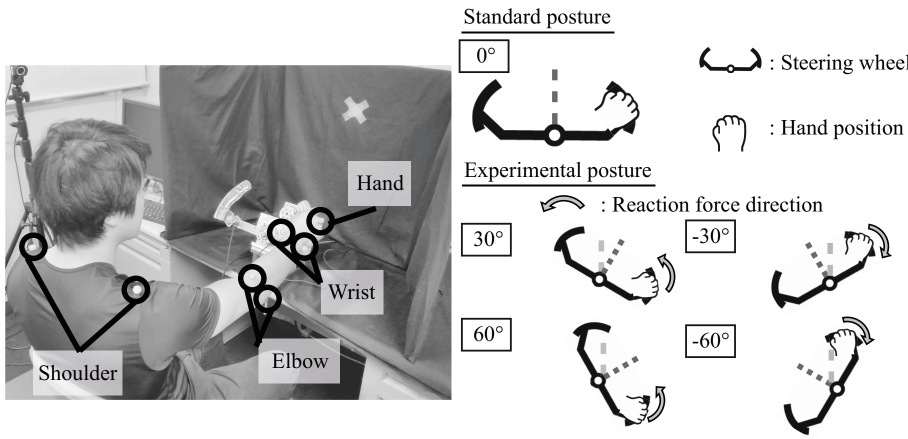


Fig. 2.1: **The simulated steering wheel device.** The device included two servo motors to generate steering wheel torque and a six-axis force sensor was attached at the base of each handgrip to obtain the exerted force from the hand. However, the experiment only used the right side grip in this experiment. It was the system used in [8]

Apparatus

A simulated steering device is used in the experiment, as shown in Fig 2.1. It was the system used in [8]. A six-axis force sensor (BL Autotec, Ltd., Micro 5/50-S09) was attached at the base of each handgrip to obtain the exerted force from the hand, and the torque presentation was generated by two servomotors (maxon motor, RE40) attached to one end of the main driveshaft. Each servomotor was attached to a 21:1 reduction gear (Harmonic Drive Systems Inc., HPG-14A-21) and a rotary encoder (Microtech Laboratory Inc., ME-20) in order to apply the desired reaction force and obtain the angle. The curved handgrips were made of acrylic plastic and formed two arcs of a circle 350 millimeters in diameter.



(a) Overview of experiment (b) Experimental postures

Fig. 2.2: **Experimental conditions.** The subject grasped the right side of the steering wheel device and memorized the reference stimulus in the reference posture(0°). Afterward, the posture changed to the experimental postures(30°, 60°, −30, −60°) and memorized the test stimuli (1.1 - 2.9 Nm, staircase method including upward step and downward step). Then, the subject was asked about the larger stimulus. The tasks were repeated 50 times(25 upward step and 25 downward steps) in each experimental posture.

Procedure

Psychophysical experiments were performed using the staircase method, which included downward step and upward step, in which the test stimuli deviates from the reference stimulus(very large and very small, respectively). In this case, very large/small means the subjects could definitely perceive the difference from the reference stimulus. These test stimuli were confirmed before the experiment. The subjects were asked to compare the magnitude of the reaction force in the reference posture and the experimental posture. They grasped the handgrip with the right hand only. Each experimental posture is shown in Fig 2.2. The reference posture was the initial position of the steering (0°), and the experimental postures were static postures of 30°, 60°, −30° and −60° from the reference. The reference stimulus was 2.0 Nm, and the experimental stimuli were changed in ascending or descending stepwise increments of 0.2 Nm between 1.1 - 2.9 Nm. The experimental postures and magnitude of each test stimulus were decided from the realistic condition [18]. The direction of the force was the same between the reference and the test stimuli. The steering wheel rotated to the left at the experimental postures of 30° and 60°, and the steering wheel rotated to the right at −30° and −60° because the direction of the steering reaction force was the same as that of the actual steering reaction force. The experimental tasks were as follows.

1. The participant grasped the handgrip with the right hand and memorized the magnitude of the reference stimulus presented in the reference position for 3 seconds. The participant maintained the posture while the stimulus was presented.

2. After changing to the experimental posture, the participant memorized the magnitude of the test stimulus presented for 3 seconds. The participant maintained the experimental posture while the stimulus was presented.

3. The participant was asked which side was larger.

4. The subsequent test stimulus was modified based on the participant ' s response.

According to the response of each trial, the test stimulus of the next trial for downward step and upward step was changed as follows.

- Answer that the test stimulus was larger than the reference stimulus: reduce the test stimulus by 0.2 Nm.

- Answer that the test stimulus was smaller than the test stimulus: increase the test stimulus by 0.2 Nm.

These procedures were used in both downward and upward step. The downward and upward step were conducted alternately. The test stimulus was repeated at the comparative stimulus of the chance level that is, near the subjective equivalence value. To avoid the effect of fatigue, a break was provided for each posture. To avoid the order effect, the order of the experimental posture was randomized for each participant. A complete experimental session for each participant consisted of 200 steering trials, with 25 upward and 25 downward steps in each posture.

Data Analysis

In the psychophysical experiment, the author calculated the perceptual bias to determine whether a perceived force with an experimental posture was perceived differently when compared with a reference posture. The percentage of responses indicating that the test stimulus was “ larger ” were calculated for each presented comparison. The percentages were plotted, and a psychometric curve was fitted to the points with a cumulative Gaussian distribution [31]:

$$f(x) = \frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{x - (2.0 + \mu)}{\sigma\sqrt{2}}\right)\right), \quad (2.1)$$

where μ and σ are the fitted parameters representing the mean and SD of the curve, respectively. Because some experimental stimuli were presented more often than others, a weighted least squares fit was used [32]. The value of μ represents the perceptual bias and $2.0 + \mu$ represents the points of subjective equality for a specific session. A positive value represents an overestimate (i.e., the reference stimulus was perceived to be larger than it actually was in the experimental posture). In contrast, a negative value represents an underestimate (i.e., the reference stimulus felt lighter in the experimental posture). The average bias for all subjects was calculated from the experimental results, and the comparison was carried out using Student ’ s t-tests (significance level: 5%) between the reference and experimental postures. Additionally, analysis of variance (ANOVA) was performed between the experimental postures, and pairwise comparisons using the Holm method were performed (significance level: 5%).

2.2.2 Muscle Activity Estimation using a 3D Musculoskeletal Model

Method

The author used OpenSim [33] to calculate the muscle activity in each experimental condition. Muscle strength was calculated using a combination of elastic and contractile elements based on Hill ' s muscle model reported by Thelen [34]. The muscle parameters, such as the maximum isometric muscle strength F^M, optimum muscle fiber length l^M, and pennation angle of the muscle, were determined according to a previous study [35]. In the muscle activity calculation, the author measured the reference posture (0°) and the experimental posture (30, 60, −30, −60°) using six motion capture systems (Optitrack, Optitrack Flex3), and joint angle and joint torque were calculated using inverse kinematics and inverse dynamics. The reflex marker was attached to the shoulder, elbow, wrist, and hand, as shown in Fig 2.2. Muscle strength was determined by optimizing the muscle activity to balance the joint torque. The m-th muscle was calculated to satisfy the following Eq. 2.2.

$$\sum_{m=1}^{n}(\alpha_m F_m^0) r_{m,j} = \tau_j. \tag{2.2}$$

F_m^0 is the isometric maximum muscle strength, τ_j is the joint torque at the j-th joint, and $r_{m,j}$ is the moment arm. α represents muscle activity and is a continuous function of $\alpha_m (0 \leq \alpha_m \leq 1)$, which can be regarded as a control signal in the musculoskeletal system [33]. Based on the relationship between the motor unit firing frequency and muscle activity, the higher the motor unit firing frequency, the greater the muscle activity [36]. The moment arm was determined by the m-th muscle length l_m and the j-th joint angle [37, 38].

$$r_{m,j} = \frac{dl_m}{d\theta_j}. \tag{2.3}$$

The following shows the relationship between muscle strength F_m and muscle activity α_m.

$$F_m = \alpha_m F_m^0 \bar{f}_l(\bar{l}_m) + F_m^0 \bar{F}^{PE}(\bar{l}_m). \tag{2.4}$$

$\bar{l}_m$ is the normalized muscle fiber length, and $\bar{f}_l(\bar{l}_m)$ is the normalized muscle strength-length relationship. The parameter of $\bar{f}_l(\bar{l}_m)$ and $\bar{F}^{PE}(\bar{l}_m)$ are used from a previous study [35].

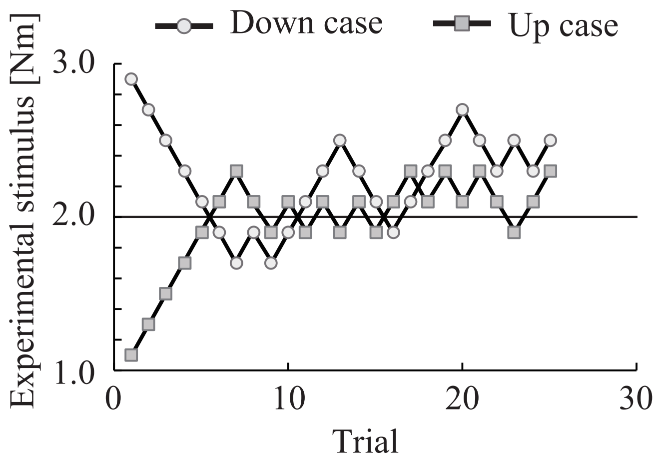
Data Analysis

In the muscle activity estimation, postural data that were obtained using a motion capture system and force data during each trial were used. In operation of the steering wheel, the previous study reported that the arm and shoulder move to make the positive tangential steering force by moving with forward elevation. For the negative tangential steering force, the arm and shoulder move in a downward direction [39]. These movements are created from the deltoid muscle (anterior, medial, and posterior), the pectoralis major muscle (upper and medial portion), the biceps brachii(long and short), and the triceps brachii (long head and lateral part). Therefore, the author used these muscles as representative muscles. This study used the average of the above-mentioned four muscles. The muscle activity differences between the experimental postures were compared using ANOVA, and pairwise comparisons were performed using the Holm method (significance level: 5%).

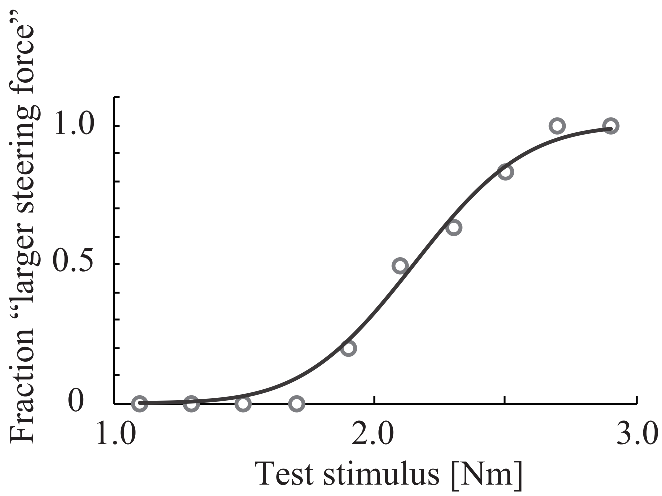
2.3 Results

2.3.1 Force Perceptual Bias

In this experiment, the author investigated the perceptual bias in driving posture using a psychophysical experiment. Fig 2.3 shows the results of the psychophysical experiments on the representative subjects. Fig 2.3(a) shows the trajectory of a given



(a) An example of the staircase in 30° of subject A



(b) An example of the psychometric curve in 30° of subject A

Fig. 2.3: **A typical result from the psychophysical experiment.** (a) shows the trajectory of a given test stimulus during the experiment on the representative subject. Each step was given 25 times. In (b), each data point shows the percentage of responses in which the test stimulus was reported as "larger", calculated for each presented comparison. The solid line shows the psychometric curve fitted to the answer plot with a cumulative Gaussian distribution using the weighted least-squares method.

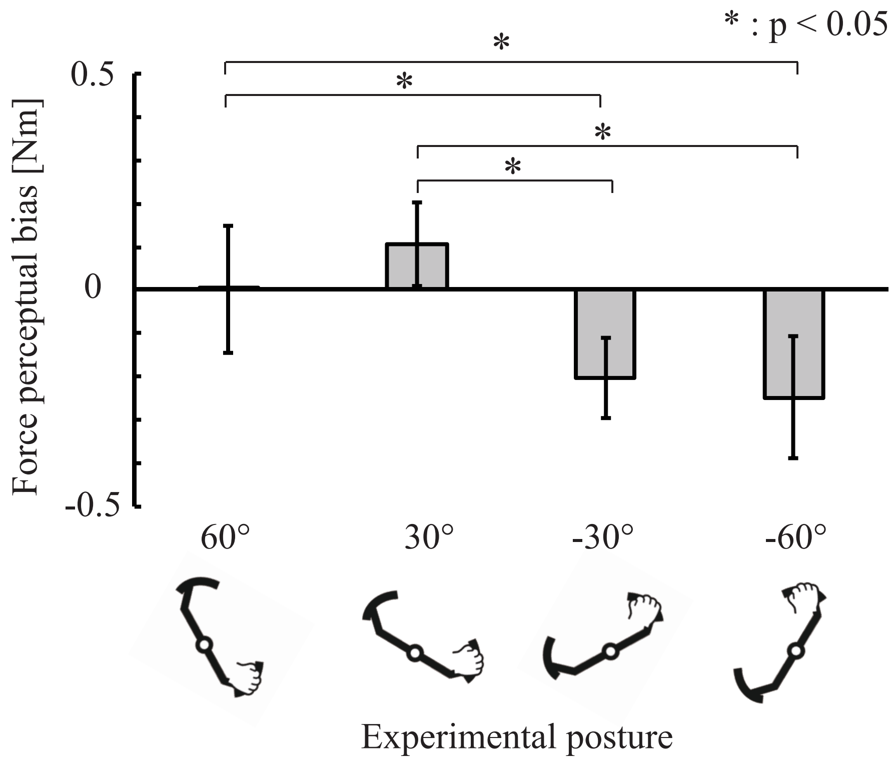


Fig. 2.4: **The result of the psychophysical experiment** A positive value represents an overestimate (i.e., the reference stimulus was perceived to be larger than it actually was in the experimental posture). A negative value represents an underestimate (i.e., the reference stimulus felt lighter in the experimental posture).

test stimulus during the experiment. It is predicted that the subject overestimated the reference stimulus because the plots are mostly located at positions larger than 2.0 . In Fig 2.3(b), a psychophysical curve was calculated using the results of Fig 2.3(a). A positive perceptual bias existed because the center of the "larger steering force"(PSE = 0.5) shifted to greater than the reference stimulus. Fig 2.4 shows the average of the perceptual bias calculated from the results of the psychophysical experiment. The bias for each posture was compared with the reference posture using Student ' s t-tests (significance level: 5%). Significant differences were found at 30° (t = 2.7, p = 0.03), $-30°$ ($t = -9.0, p < 0.001$), and $-60°$ ($t = -6.5, p < 0.001$). No significant differences were observed at 60° ($t = 0.16, p = 0.9$). An ANOVA revealed significant

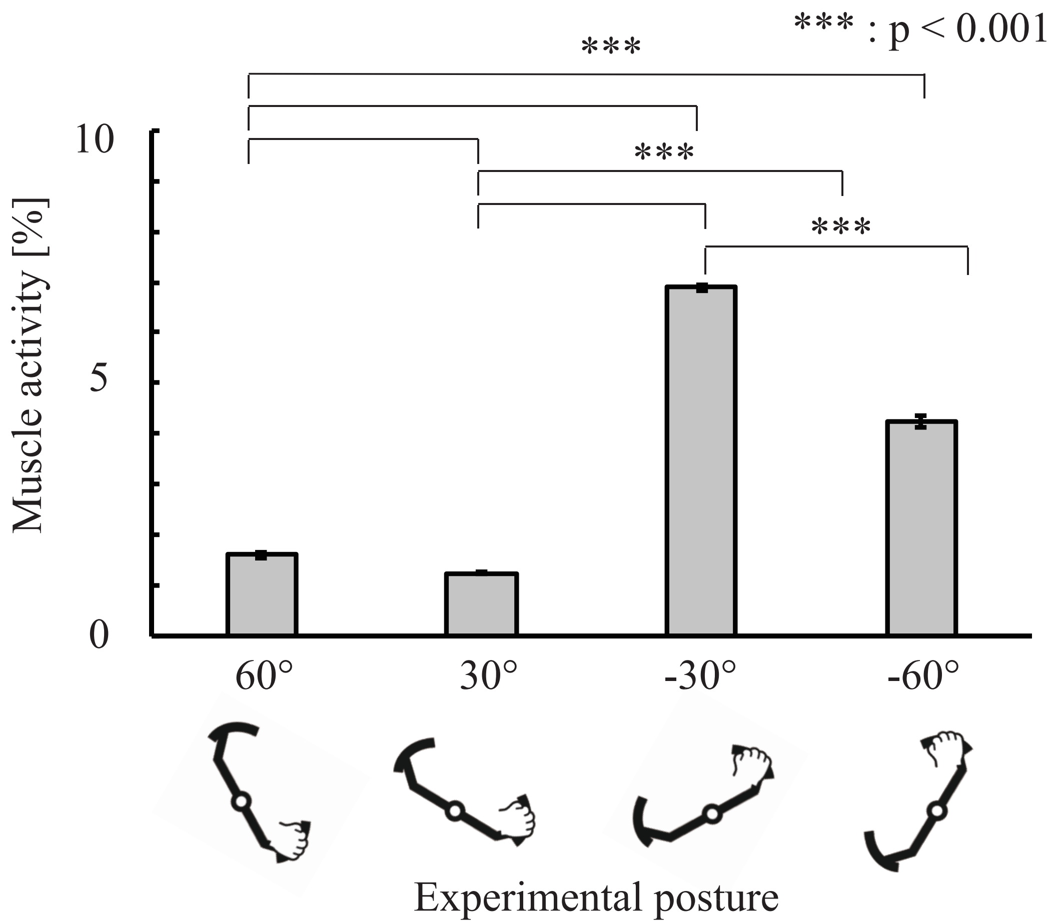


Fig. 2.5: **Mean muscle activity for each angle in all participants (with a stimulus of 1.9 Nm).** The 1.9 Nm test stimulus was used as a force value in the muscle activity estimation because this stimulus trial was the most common across all participants and postures.

differences ($F_{1,8} = 28.3, p < 0.001$) between each experimental posture. In pairwise comparisons, significant differences were observed at 30° versus $-30°(t = 9.4, p < 0.001)$, 30° versus $-60°(t = 7.2, p < 0.001)$, 60° versus $-30°(t = 4.7, p = 0.002)$, and 60° versus $-60°(t = 4.1, p = 0.01)$. No significant differences were observed at 30° versus $60°(t = 2.6, p = 0.06)$ and $-30°$ versus $-60°(t = 1.3, p = 0.2)$. The results show that perceptual bias existed in each experimental posture except for 60˚. Additionally, it was shown that there is a significant difference in the size of the bias based on the

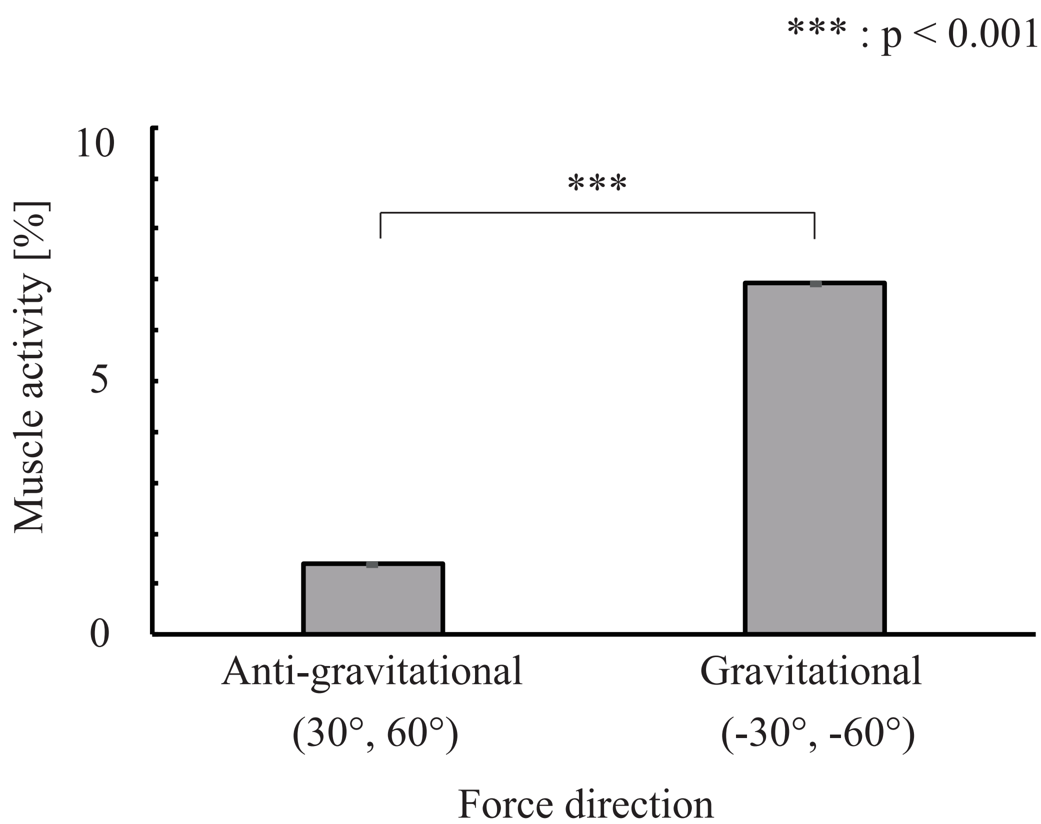


Fig. 2.6: **Mean muscle activity of reference angle in all participants.** In 30° and 60°, the anti-gravitational force is given for the reference force in the 0° posture, and the gravitational force is given for the reference force in the 0° posture in −30° and −60°. The Welch's t-test showed a significant difference between the directions of the force($t = -1.93 * 10^2, p < 0.001$).

posture.

2.3.2 Muscle Activity Estimation

The psychophysical experiment showed that perceptual biases existed in the experimental postures (except for 60 °). To further investigate the perceptual bias, the author estimated the muscle activity in the experimental postures. Fig 2.5 shows the representative results of the muscle activity estimation. As a representative results, 1.9 was chosen because it was found most frequently among all subjects in the experiment.

An ANOVA revealed significant differences ($F = 1.2 * 10^3, p < 0.001$) between each experimental posture. In pairwise comparisons, significant differences were observed at 30° versus 60°($t = -3.35, p < 0.001$), 30° versus −30°($t = -52.2, p < 0.001$), 30° versus −60°($t = -27.1, p < 0.001$), 60° versus −30°($t = -49.7, p < 0.001$), 60° versus −60°($t = -24.3, p < 0.001$), and −30° versus −60°($t = 25.0, p < 0.001$). Fig 2.6 shows the muscle activity estimation result of the reference angle. These muscle activities are compared using Welch ’ s t-tests (significance level: 5%). The result showed a significant difference between the directions of the force($t = -1.93 * 10^2, p < 0.001$). These results indicate that muscle activity varied with posture, suggesting that muscle activity affected differences in the perceptual bias.

2.4 Discussion

The results revealed significant differences when compared with the reference posture (i.e., force perceptual bias was caused by changing the posture) in all positions except for 60°. Additionally, the muscle activity estimation was also carried out in each trial. As shown in Fig 2.5, muscle activity varied depending on the posture, even when the same stimulus was presented to participants. Jones reported that when the weight of an object is discriminated, the relative size is perceived and scaled by the range of muscle activities involved in motion [13, 40]. This finding indicates that high muscle activity could potentially cause perceptual bias.

The results of the psychopsysical experiment revealed a significant difference between postures, as shown in Fig 2.4. Additionally, significant differences existed between the anti-gravitational and gravitational directions, as shown in Fig 2.6. These results suggest that the force direction during the trials affected the perceptual characteristics, similar to the results of Sakajiri et al., who reported an effect of whether the force direction was in the gravitational direction or not [8].

Human somatic sensation is known to change depending on whether the direction of the force is in the gravitational direction or not, and many studies have examined the effects of gravity. In the field of developmental psychology, Hood et al. report that infants learn the effect of gravity on objects as they age [41]. People move on the assumption that there is gravity [42], and the weight discrimination threshold rises in zero-gravity space [43]. In addition, Young et al. report that the positional sense of the body is lost, and motor skill decreases, when subjects operate in the absence of vision under zero-gravity space conditions [44]. The direction of the reaction force changes depending on the rotating direction in steering and becomes the anti-gravitational direction depending on the position of the arm. In the 30 ° and 60 ° conditions, the force direction is anti-gravitational because only the right hand gripped the steering wheel in this experiment. The reaction force can be offset by the arm ' s own weight in the anti-gravitational direction. Therefore, the muscle activity becomes low at 30° and 60°. Perceptual bias would also be expected to be affected by the difference in muscle activity with the direction of force.

2.5 Concluding Remarks

In the current study, the author investigated whether force perceptual bias depends on posture while steering using a psychophysical experiment. The results revealed bias at postural angles of 30 ° , − 30 ° , and − 60 ° . These findings suggested that muscle activity increases by changing the posture and direction of the reaction force. In future studies, the author plan to test steering reaction force conditions considering this perceptual bias, to investigate the relationship with the sensation of steering.

Chapter 3

Prediction of Perceived Force from Muscle Activity during Steering-Wheel Operation

3.1 Introduction

The rest of the Chapter is organized as follows. Section 2.2 describes the force-perceptual characteristics observed in operating a steering-wheel. Section 2.3 explains the method of estimating the muscle activity based on the 3D musculoskeletal model. In Section 2.4, the result of the muscle-activity estimation, and the method of predicting the perceived force are detailed. In addition, the prediction results are evaluated. Section 2.5 simulate the pshychophysical experiment by using perceived force prediction model. Section 2.6 discusses the results. Finally, Section 2.7 presents our conclusions and future work.

3.2 Force-Perceptual Characteristic of Humans during Steering-Wheel Operation

We investigated the force-perceptual characteristics of humans while the postures of 0, 30, 60, and 120° in steering-wheel operation. We used the same system reported

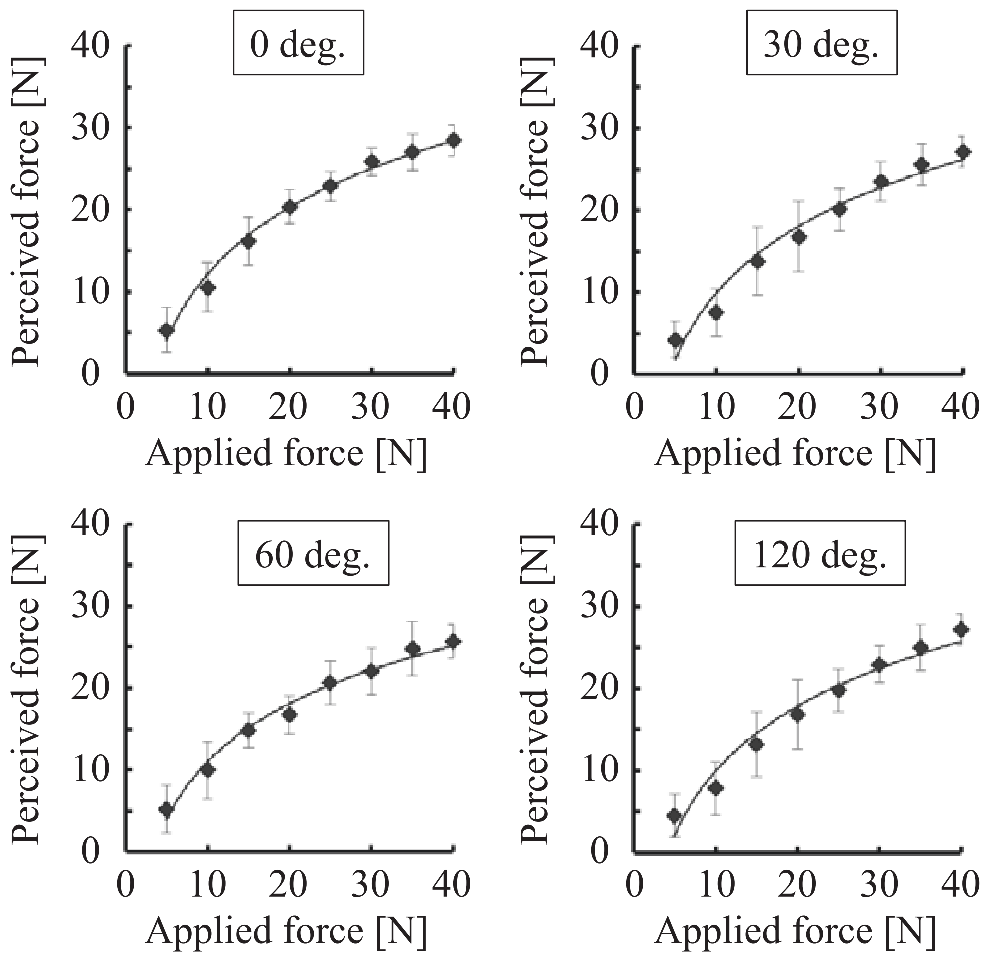


Fig. 3.1: The force-perceptual characteristics of humans while the postures of 0, 30, 60, and 120° in steering-wheel operation by magnitude estimation experiment. The solid curve indicates the approximate curve.

in [16]. The equipment mainly consisted of three parts: (1) a direct-drive rotary motor (M-YSB, NSK, Ltd.; maximum output torque: 20 Nm), (2) a computer to perform a motor control, and (3) a display to show the angle of the steeringwheel. The force applied to the steering-wheel by the subjects was measured with a force transducer (TR60, Comprehensive Instrumentation; rated torque: 50 Nm) embedded in the steering-wheel. The angle of the steering-wheel was measured by an encoder (resolution: 51,200 pulse/rad) built in the motor. The motor control was done by a

DSP board (ds1103, dSPACE). A measurement experiment to determine the subjects' subjective force perception was conducted based on magnitude estimation [45]. The experimental procedure was as follows:

1. In the experimental posture, the subjects sat on the seat and held the steering-wheel by their hands. After the participants griped the steering-wheel, a standard stimulus (20 N) was given through the steering-wheel in a counterclockwise direction. Subjects keep the steering-wheel in a first posture. The experimenter asks the participants to memorize a standard stimulus in five sec. In our pre-experiment, we found that the habituation was occurred when displaying force more than five sec. In order to avoid the error of habituation [46], we decided five sec. for stimulus duration.

2. With the subjects' posture kept, the steering-wheel reaction force was gradually increased for four seconds, and for five more seconds with fixed steering wheel-reaction force thereafter.

3. The participants were asked to determine the perceived force using the magnitude-estimation method.

Four male subjects aged from 22 to 45 were participated the experiment. Instructions were given prior to perform the tasks. We obtained informed consent, and asked the health condition in verbally by the subjects. When the health condition was not good, we changed the experimental date. The standard stimulus was applied once first, and the comparison stimuli were then applied three times at random. The subjects were asked to answer the scale of the perceived reaction forces from eight comparison stimuli ranging from 5 to 40 N (5 N increment) in relation to a standard stimulus of 20 N. The comparison stimuli were applied five times with each reaction force for a total of 40

Table 3.1: Coefficient a_i and b_i

i	a	b
0	11.74455	−14.9079
30	11.69816	−16.97800
60	10.20344	−12.47222
120	11.37027	−16.17813

times. The experimental postures were 0, 30, 60, and 120°. The neutral position was set as 0°, and 30, 60, and 120° mean that the steering wheel was turned to the right from 0°. We asked the subjects to practice the experiment about 10 minutes before the experiment. Fig. 3.1 shows the results of the experiment. The solid curve indicates the approximate curve. The results suggest that the perceived force is proportional to the logarithm of the applied force. This characteristic follows Weber–Fechner law [17]. Accordingly, the perceived force of a human F_p is approximated using the following equation:

$$F_p = a\log F_a + b \tag{3.1}$$

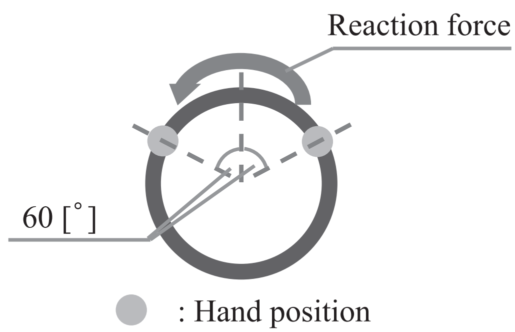
where F_a is the applied force, and a_i and b_i are coefficients obtained using the least square method, presented in Table 3.1. i is the steering-wheel angle (i = 0, 30, 60, and 120). Since there is no clear difference between the applied force and the perceived force for these postures in Fig. 3.1, we used the 0° posture as the typical characteristics in this study. Here, we define the perception-change ratio P of the perceived force as follows:

$$P = \frac{F_p}{F_a} = \frac{a\log F_a + b}{F_a}. \tag{3.2}$$

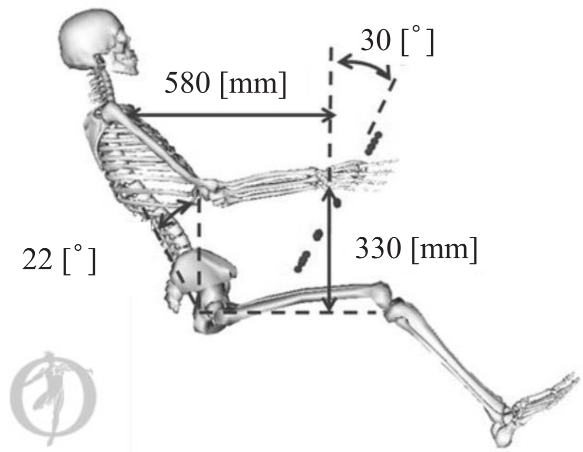
In this equation, the force perception-change ratio is determined uniquely using the external applied force. However, Takemura et al. reported that the perceived force changes depending on the body posture [16]. As described in chapter 1, humans sense the amount of force based on the sense of effort [22], and the muscle activity can be used as an inferential estimate of effort [23]. This strongly suggests that the perceived force is affected by the muscle activity. To evaluate the muscle activity, the normalized surface electromyography is employed using a maximum voluntary contraction (%MVC). However, it cannot be ensured that the subjects would exert true maximum voluntary force. Moreover, the limitation of measurable muscles with a certain level of accuracy is an issue. One of the drawbacks of surface electromyogram measurement (sEMG) is that its surface electrodes have a limited spatial resolution and detect, therefore, only a superposition of a very large number of muscle motor units. Moreover, sEMG recordings can indicate when a muscle is active, but examination of sEMG recordings does not allow one to determine which motions of the body arise from a muscle ' s activity [33]. As another method, the muscle activity can be evaluated by simulating a musculoskeletal model simulation. A musculoskeletal model simulation is a noninvasive method used to calculate the muscle activity. The musculoskeletal model simulation was used to estimate the force in the upper extremity [35], muscle activity in the swing phase of gait [47] and how the muscles contribute to body weight support and propulsion [48,49]. In this study, we try to express the force perception-change ratio using the muscle activity that is computationally estimated using the 3D musculoskeletal model.

3.3 Muscle Activity Estimation using 3D Muscloskeletal Model

The author used OpenSim [33] to calculate the muscle activity in each experimental condition. Muscle strength was calculated using a combination of elastic and contractile elements based on Hill ' s muscle model reported by Thelen [34]. The muscle parameters, such as the maximum isometric muscle strength F^M, optimum muscle



(a) Steering-wheel condition.



(b) Model posture condition.

Fig. 3.2: Simulation conditions

fiber length l^M, and pennation angle of the muscle, were determined according to a previous study [35]. In the muscle activity calculation, the author measured the reference posture (0°) and the experimental posture (30, 60, −30, −60°) using six motion capture systems (Optitrack, Optitrack Flex3), and joint angle and joint torque were calculated using inverse kinematics and inverse dynamics. Muscle strength was determined by optimizing the muscle activity to balance the joint torque. The m-th muscle was calculated to satisfy the following Eq. 3.3.

$$\sum_{m=1}^{n}(\alpha_m F_m^0) r_{m,j} = \tau_j. \tag{3.3}$$

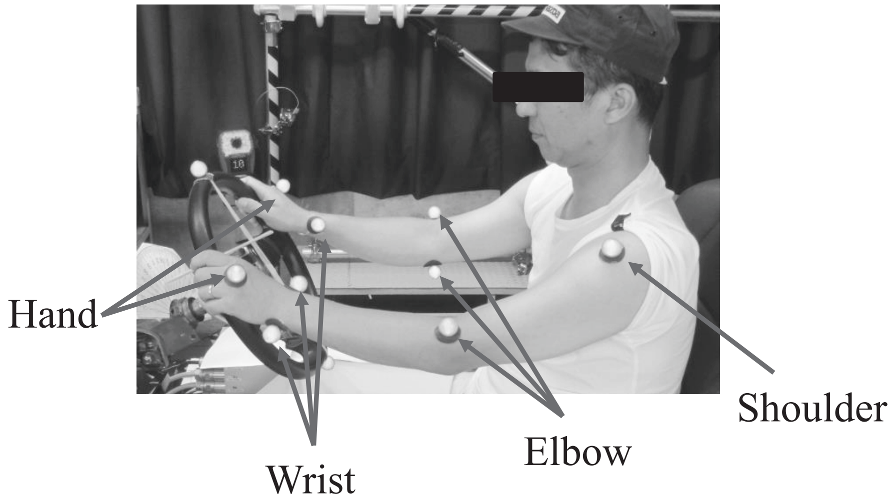


Fig. 3.3: Motion capturing system condition.

F_m^0 is the isometric maximum muscle strength, τ_j is the joint torque at the j-th joint, and $r_{m,j}$ is the moment arm. α represents muscle activity and is a continuous function of $\alpha_m (0 \leq \alpha_m \leq 1)$, which can be regarded as a control signal in the musculoskeletal system [33]. Based on the relationship between the motor unit firing frequency and muscle activity, the higher the motor unit firing frequency, the greater the muscle activity [36]. The moment arm was determined by the m-th muscle length l_m and the j-th joint angle [37,38].

$$r_{m,j} = \frac{dl_m}{d\theta_j}. \tag{3.4}$$

The following shows the relationship between muscle strength F_m and muscle activity α_m.

$$F_m = \alpha_m F_m^0 \bar{f}_l(\bar{l}_m) + F_m^0 \bar{F}^{PE}(\bar{l}_m). \tag{3.5}$$

$\bar{l}_m$ is the normalized muscle fiber length, and $\bar{f}_l(\bar{l}_m)$ is the normalized muscle strength-length relationship. The parameter of $\bar{f}_l(\bar{l}_m)$ and $\bar{F}^{PE}(\bar{l}_m)$ are used from a previous study [35].

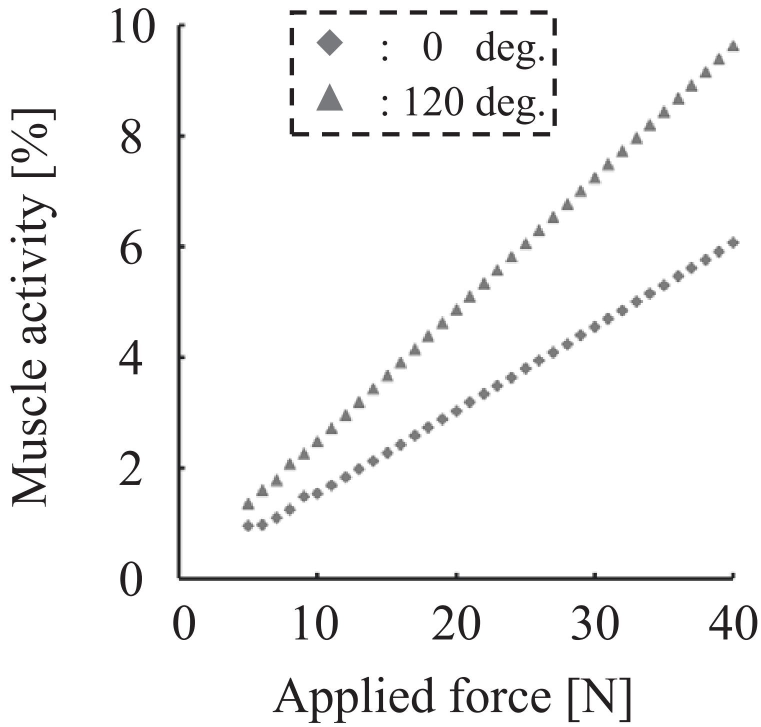


Fig. 3.4: The representative estimation results of the muscle activities that actively work when holding the steering-wheel. Diamonds indicate 0°, and triangles indicate 120° of the steering-wheel angle.

3.4 Estimation of Muscle Activity and Perceived Force during Steering-Wheel Operation

3.4.1 Condition of Simulation

We calculated the muscle activity while operating the steering-wheel under the same condition as that given in the study by Takemura et al [16]. Fig. 3.2 shows the simulation conditions. The positions of the left and right hands were placed at −60 and 60°. We obtained the posture data between 0 to 120° of the steering-wheel angle with an interval of 10° using 12 motion capture cameras (MAC3D System, NAC Image Technology Inc.) placing around the subject, mounted one marker on the shoulder, wrist, and hand, and two markers on the elbow of each arm (Fig. 3.3). The forces

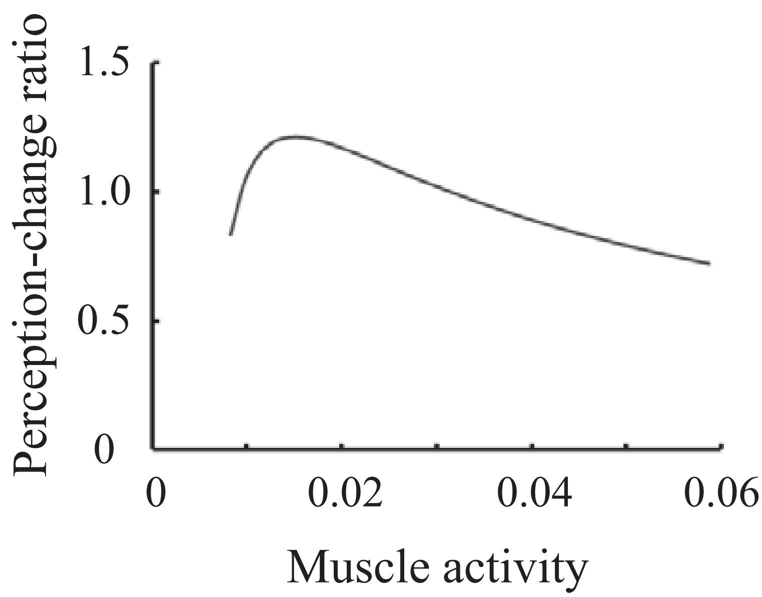


Fig. 3.5: The change in the perception-change ratio with respect to the muscle activity.

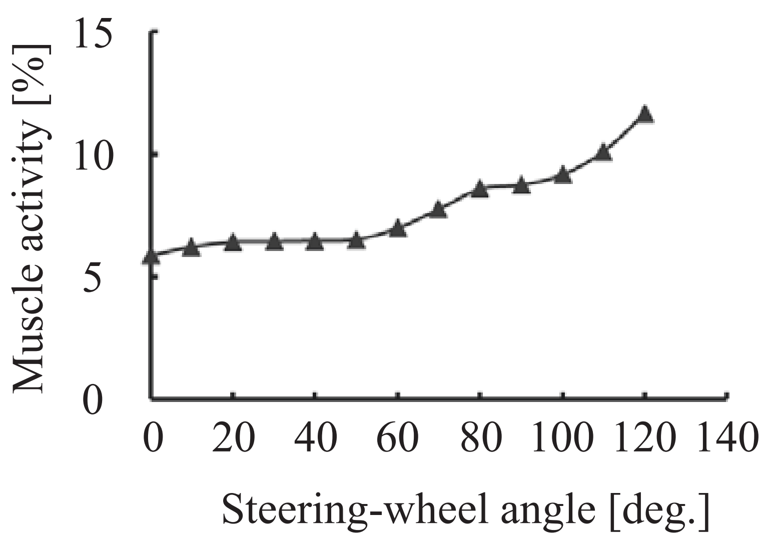


Fig. 3.6: Relationship between the muscle activity and the steering-wheel angle (10 N is applied on each arm).

ranging from 5 to 20 N with an interval of 1 N interval were applied to each arm in the simulation.

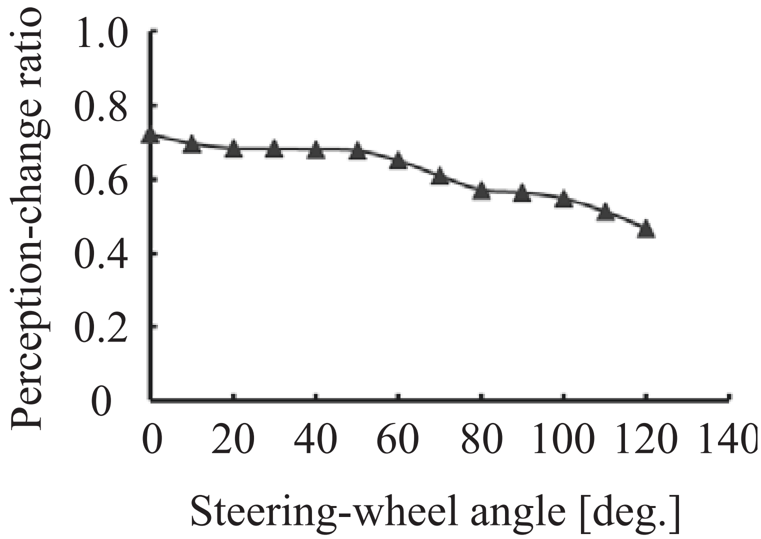


Fig. 3.7: Relationship between the steering-wheel angle and the perception-change ratio (10 N is applied on each arm).

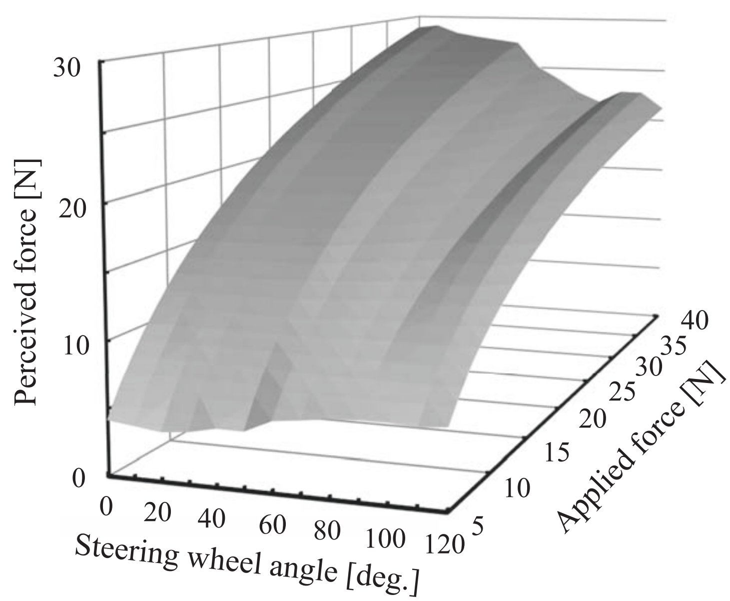


Fig. 3.8: Predicted perceived force with respect to steering-wheel angle and applied force.

3.4.2 Perception-Change Ratio

Fig. 3.4 shows the estimation results of the representative muscles that actively work while the postures of 0, 30, 60, and 120° with holding a steering-wheel. Steering motion can be anatomically described as forward elevation of the arm and shoulder, which creates positive tangential steering forces, and downwards depression of the arm and shoulder to generate negative tangential steering forces [39]. Muscles involved in forward elevation of the arm and shoulder are the anterior and medial of the deltoid muscle, upper portion of the pectoralis major muscle, and the long and short of the biceps brachii. Muscles involved in downward depression of the arm and shoulder are the medial of the pectoralis major, and possibly the posterior deltoid and the long head and lateral of the triceps brachii. Therefore, we used pectoralis major muscles (upper, medial), deltoid muscle (anterior, medial, posterior), triceps brachii muscles (lateral, long), and biceps brachii muscles (long, short) as the representative muscles. The horizontal and vertical axes represent the applied force and muscle activity, respectively. The applied force Fa is expressed using muscle activity a as follows:

$$F_a = G(\alpha) \tag{3.6}$$

Fig. 3.5 shows the linear relationship between the applied force and the muscle activity. Accordingly, we obtain the following equation.

$$\alpha = k_i F_a + m_i \tag{3.7}$$

k and m are the coefficients obtained using the least-square method between 5 to 40N. j is the steering-wheel angle (j = 0, 10, 20,..., and 120) which is given in Table 3.2. Table 3.3 lists the coefficient values in Eq.3.7. By substituting Eq.3.7 into Eq.3.2, we obtain the following equation.

$$P = \frac{F_p}{F_a} = \frac{k_0\left(a_0 \log\left(\frac{\alpha - m_0}{k_0}\right)\right) + b_0}{\alpha - m_0}. \tag{3.8}$$

This equation shows that the change ratio of the perceived force can be expressed as a function of the muscle activity. Here, we used k_0 and m_0, which are obtained at 0°, to calculate the perception-change ratio. Fig.3.6 shows the change in the perception-change ratio with respect to the muscle activity. We can see the perception change ratio peaks at a muscle activity of 1.5 percent, and subsequently, it gradually decreases with the increase in the muscle activity. By using this relationship, we can obtain the perceived force of a human by inputting the steering angle and applied force. Here, we calculated the muscle activity for each steering-wheel angle for a force of 10 N applied to each arm. Fig. 3.7 shows the obtained muscle activity in each posture using Eq.3.7 and the coefficients in Table 3.2 with applying 10N on each arm. This figure indicates that the muscle activity changes depending on the posture even if the given force is same. By substituting the obtained muscle activity into Eq.3.7, the perception-change ratio of force was determined. Fig. 3.8 shows the obtained perception-change ratio in each posture. By using the obtained perception-change ratio, the perceived force F_p can be predicted using the following equation.

$$F_p = P \cdot F_a \tag{3.9}$$

Table 3.2: Coefficient value of k_j and m_j

j	k_j	m_j
0	0.00150	0.00059
10	0.00143	0.00042
20	0.00151	0.00020
30	0.00154	0.00018
40	0.00156	0.00044
50	0.00158	0.00053
60	0.00183	0.00079
70	0.00198	0.00063
80	0.00217	0.00058
90	0.00230	0.00058
100	0.00213	0.00107
110	0.00215	0.00056
120	0.00238	0.00056

Table 3.3: Coefficients of determination

j	R_i^2
0	0.9996
10	0.9999
20	1.0000
30	1.0000
40	1.0000
50	1.0000
60	1.0000
70	1.0000
80	1.0000
90	1.0000
100	1.0000
F 110	1.0000
120	1.0000

We calculated the muscle activity for forces ranging from 2.5N to 20N applied to each arm with an interval of 0.5N. Fig. 3.9 shows the calculated relationship between the steering-wheel angle, applied force Fa, and perceived force F_p. This figure indicates that the proposed method can be used to successfully show the posture-dependent characteristics of the perceived force.

3.4.3 Evaluation

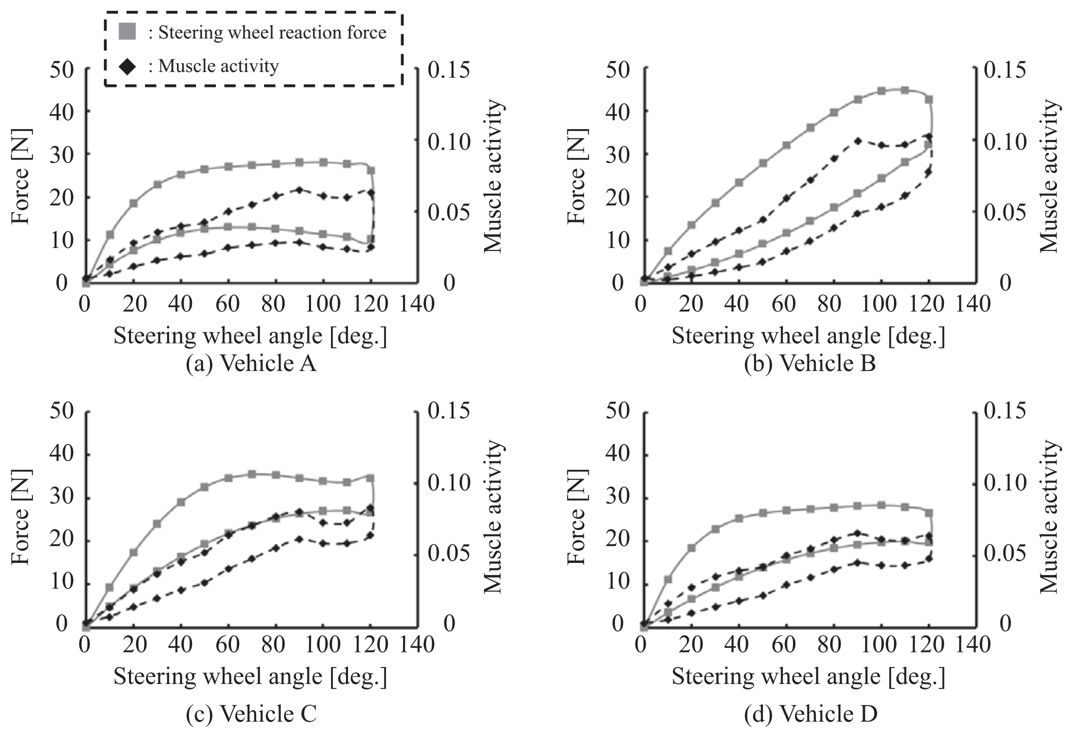


Fig. 3.9: Muscle activity characteristics of the steering-wheel. Squares indicates the measured steering-wheel reaction force using force sensor. Diamonds indicates the muscle activity by Eq.3.7.

We evaluated the performance of the proposed method by predicting the perceived force for four different vehicles, which are commercially available. First, we measured the steering-wheel-reaction force for the four vehicles. Fig. 3.10 shows the measured

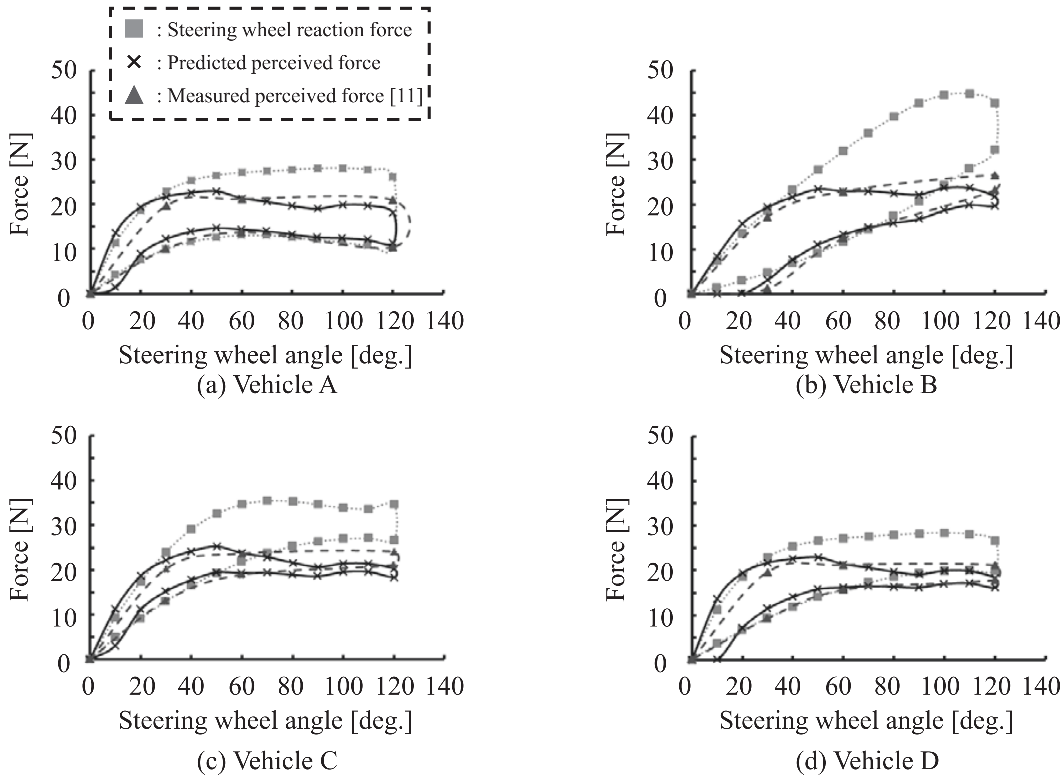


Fig. 3.10: The predicted perceived force with respect to the steering-wheel angle. Squares indicate the measured reaction force of the steering wheel. Crosses indicate the predicted perceived force. Triangles indicate the mean perceived force by experiment. The measured reaction force by a torque sensor by human subjects when a subject holds the steering-wheel from 0 to 120° in a clockwise direction, and from 120 to 0° in a counterclockwise direction. The predicted perceived force obtained by Eq.3.9. The perceived force obtained by using magnitude-estimation experiment while the postures of 0, 30, 60, and 120° in a clockwise and counterclockwise direction.

relationship between the steering-wheel angle and the reaction force exerted while the postures from 0 to 120° with an interval of 10°. By using Eq.3.7, we can obtain the muscle activity that balances the steering-wheel-reaction force. The dashed lines in the figure indicate the estimated muscle activity. Next, we calculated the perception-change ratio and the perceived force Fp using Eqs.3.8 and 3.9. Fig. 3.10 shows the predicted perceived force with respect to the steering-wheel angle. We plotted the mean perceived force, which is calculated using the experimental results [16] shown in Fig. 3.10, to compare with the predicted perceived force. We used the spline interpolation for the mean perceived forces by experiment because the measured angles are limited in the experiments (0, 30, 60, and 120°).

We then computed the mean of the absolute error E_j between the predicted and measured the perceived force to confirm the accuracy, where j is the type of vehicle (i = A, B, C, and D). The following are the error values: $E_A = 1.46$, $E_B = 2.18$, $E_C = 1.89$, and $E_D = 1.58$N. In addition, we computed the Maximal Information Coefficient (MIC) [50] between the mean perceived force by experiment and the predicted perceived force. MIC indicates the index of the correlation by the value of 0 (no correlation) to 1 (with correlation). The following are the MIC_i: $MIC_A = 0.89$, $MIC_B = 0.93$, $MIC_C = 0.79$, and $MIC_D = 0.84$. These results suggest that the proposed method can be used to computationally predict the subjective sense of force exerted while operating the steering-wheel of a vehicle.

3.5 The Simulation of Psychophysical Experiment

3.5.1 Method

The author predicted the perceptual bias in each posture using the perceived force prediction model. First, muscle activity was estimated using the stimulus force data and posture (reference and test, respectively) in psychophysical experiment(Chapter 2). The F_p values were then estimated in both conditions, and a comparison was carried out. In cases where the F_p of the test stimulus was larger than that of the reference stimulus, the author recorded the response as "larger". The calculation method of the force perceptual bias followed the technique described in the Chapter 2's "Perceptual Bias" chapter , and the predicted force perceptual bias $\mu_{predict}$ was calculated. The

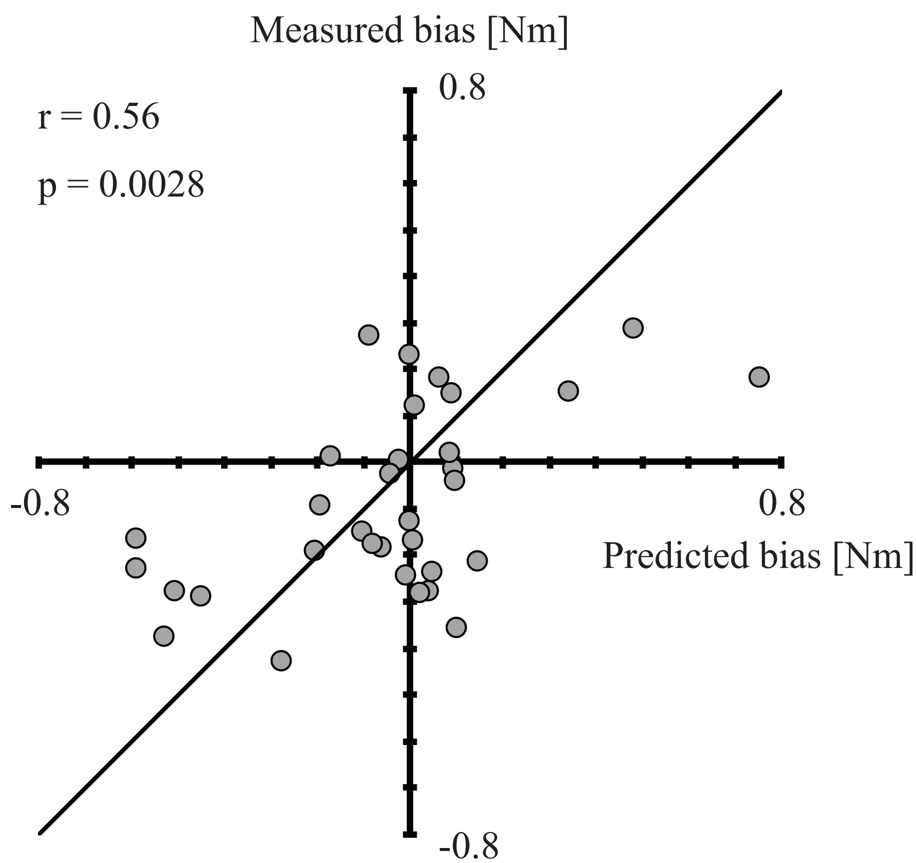


Fig. 3.11: **The scatter plots show the predicted bias from the calculation and the measured bias from the psychophysical experiment.** The solid line is the line of equality, where the predicted bias and measured bias exactly matched. The author obtained a significant moderate correlation ($r = 0.56, p = 0.0028$).

accuracy was verified by obtaining the correlation coefficient between the true value and the predicted value.

3.5.2 Result

Fig 3.11 shows the plots between the predicted bias $\mu_{predicted}$ and the measured bias. The author obtained a significant, moderate correlation ($r = 0.56, p = 0.0028$).

3.6 Discussion

3.6.1 The Perceived Force Prediction Model

Conventionally, the perceived force was obtained by conducting experiments on humans. However, it is difficult to perform the experiment for all the steering-wheel angles because the time required to complete the experiment would be considerable. Our method enables to computationally predict the perceived force under any force and posture conditions. The difference in the posture and the reaction force are reflected in the muscle activity by the muscle activity simulation. Since the reaction force from the steering-wheel are different between from 0 to 120° and from 120 to 0°, the obtained muscle activities are also different even if the postures are same. As shown in Fig. 3.8 the perception-change ratio peaks at a muscle activity of 1.5 percent, and subsequently, it gradually decreases with the increase in the muscle activity. McCloskey et al. reported that sense of force is affected by sense of effort [22]. In addition, there is a positive correlation between the muscle activity and sense of effort [24]. Therefore, we considered that the perceived force is affected by the muscle activity.

Table 3.4 shows the comparison of the MIC between the true and the predicted values which are reported in [10] and the proposed method. We obtained good correlation values around 0.8 from the proposed method. In the previous method, human experiments in that human subjects were asked to answer the perceived force for every steering-wheel angle were required to calculate the perceived force. In contrast, the proposed method can predict the perceived force by the musculoskeletal simulation without subjective experiments.

However, the accuracy of predicting the perceived force depends on the accuracy of estimating the muscle activity using the musculoskeletal model. First, muscle co-contraction is neglected in estimating the muscle activity using our method. We can control the joint stiffness with co-contraction of the muscles [51] and realize accurate movements [52, 53]. Improving the method of estimating the muscle activity by considering the muscle co-contraction is very important to improve the prediction performance. Osu et al. demonstrated that co-contraction decreases gradually over the course of learning a novel motor task [54]. The current method may be effective in situations wherein users are sufficiently accustomed to the motions. In other words, it is possible to improve accuracy by reducing the effect of co-contraction by setting experimental conditions under which co-contraction does not occur, or by selecting subjects who are familiar with such motor tasks. Second, in our method, the muscle activity is estimated considering a static driving posture. However, dynamic motions are observed while operating the steering-wheel of a vehicle. Mitchell reported that the dynamic exercise involves changes in muscle length and joint movement with rhythmic contractions, which develop a relatively small intramuscular force; static exercise involves development of a relatively large intramuscular force with little or no change in the muscle length or joint movement [55]. Hence, the muscle-exerting characteristics are different with respect to the static and dynamic movements. A sophisticated algorithm is required for estimating the muscle activity to address these issues. Third,we assumed that each arm generates equal forces to operate the steering-wheel. In practice, the force are not equal. Sakajiri et al. and Tanaka et al. have reported that subjects exerted greater forces in the gravitational direction while operating steering-wheel, and the forces exerted by the arm and motor control are different [8, 56]. Moreover, the exerted forces depend on the condition of the road [57]. Considering these human characteristics during vehicle operation helps in improving the prediction performance. The proposed method has a lower experimental cost than that of the conventional method with human experiments.

Table 3.4: Comparison of the obtained correlation coefficients between true and the predicted values which are reported in [10] and the proposed method.

	R_A	R_B	R_C	R_D
Result reported in [10]	0.98	0.99	0.98	0.95
Proposed method	0.96	0.98	0.96	0.96

3.6.2 The Bias Prediction

The author conducted a psychophysical simulation experiment to predict bias using estimated muscle activity from postures and arm force data during the experimental tasks. The results revealed a significant moderate correlation between the predicted bias and the actual bias, indicating that human force discrimination could be predicted relatively accurately based on the psychophysical experimental simulation. Since only the estimated muscle activity was used, the prediction made it easier to examine the bias, compared with the experimentally determined muscle activity. Additionally, from the perspective of the force perception mechanisms of the body, it is possible to explain the bias based on muscle activity. Consideration of perceptual bias in steering is useful for designing steering reaction force, and the improvement of operability could play an important role in preventing operational error.

In recent years, however, it has been reported that afferent signals from muscle spindles and skin receptors in the periphery are also important factors in determining sense of force/heaviness [1, 58, 59]. Although it has been confirmed that the sense of effort can be used for judging force/heaviness, an influential current hypothesis predicts that judgments of force/heaviness are based not only on sense of effort but also on feedback of afferent signals returning from the periphery [60]. Monjo et al. propose that humans do not perceive signals of only efferent or afferent signals as sense of effort but can perceive effort by changes in weight between both signals according to the experimental conditions [61]. The present experiment did not include conditions such as paralysis of muscle spindles. However, as Proske et al. report, it is necessary to provide participants with proper instructions when examining either efferent or afferent signals alone [1]. Since the prediction is carried out only by the muscle activity interpreted as the efferent signal, the afferent signals, such as sensing information from the muscle spindle and cutaneous sensation, which can be considered afferent feedback, appear to affect the prediction accuracy.

Additionally, although the range of steering reaction force is the same in the estimation model, the model was based on psychophysical experiments using both hands. Therefore, the current model cannot be completely applied in this case.

3.7 Concluding Remarks

We developed a computational method to predict the perceived force by evaluating the muscle activity as a function of effort in the operation of a steering wheel. First, we estimated the muscle activity using a musculoskeletal model with a static driving posture. Second, we predicted the perceived force while operating the steering-wheel for angles ranging from 0 and 120°. These results revealed that the perceived-force characteristics depend on the driving posture, though the applied force is the same. Third, we evaluated the results, and showed that the mean of the absolute error is 1.78 N for the experiments conducted on four different vehicles. Finally, the author predicted the force perceptual bias using muscle activity during the experimental task and obtained a significant moderate correlation between the predicted and measured bias. The results of the prediction indicated that it is possible to predict perceptual bias with relatively high accuracy using muscle activity, interpreted as sense of effort. In future, we will obtain the grip force and, external-force distribution in each arm, and consider the detailed physical capacity of the driver.

Chapter 4

Development the Haptic Suit by using Artificial Muscle to Change the Subjective Weight/Force Perception

4.1 Introduction

The rest of the Chapter is organized as follows. Section 4.2 describes concept of haptic suit and the detail of pneumatic gel muscle. Section 4.3 explains the method of experiment. In Section 4.4, the author discuss about the result of the experiment. Finally, Section 4.5 presents our conclusions and future work.

4.2 Haptic Suit

4.2.1 Concept

It is said that sense of effort, which is the size of motor command sent from the center of the brain to the muscle in the periphery, is one of the important elements for the sense of force/weight. [21]. When muscles are fatigued or paralyzed, it is necessary to send larger commands to compensate for the insufficient force, which causes them to feel heavier. It has been reported that sense of effort and sense of force/weight are directly linked. [1, 20, 22]. And, since sense of effort is highly correlated with the magnitude of the muscle activity [23, 24], it is possible to change the subjective perceived force/sense by changing the muscle activity. Then, in this suit, the artificial muscle can be mounted to cross the joint, and the suit which changes the sense of weight by assisting/resisting the motion by generating the torque.

4.2.2 Pneumatic Gel Muscle

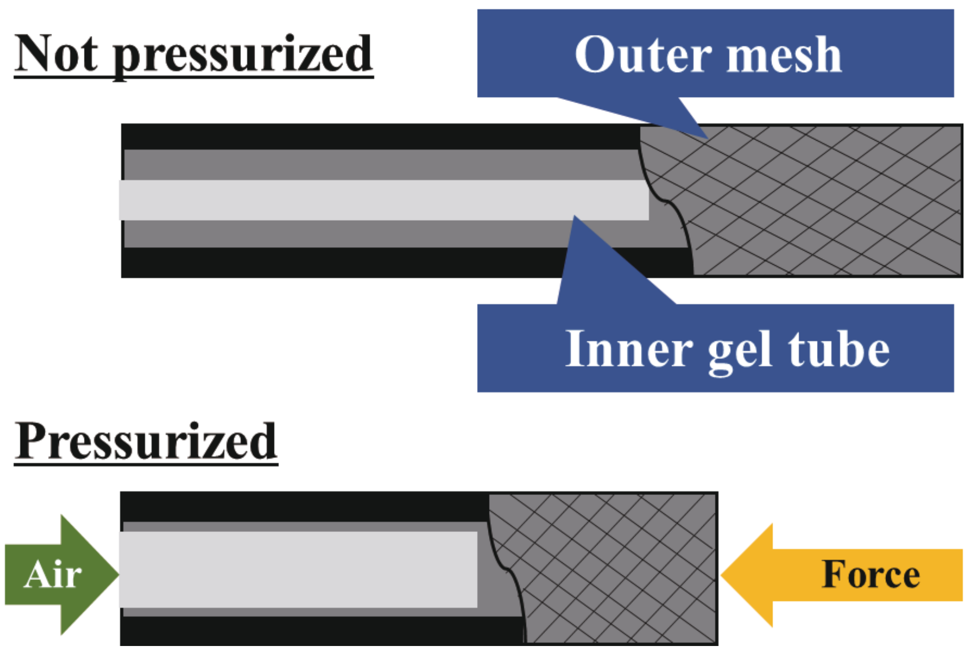


Fig. 4.1: PGM overview

In this study, low pressure drive McKibben rubber pneumatic artificial muscle (Pneumatic gel muscle: PGM) is used. That is developed by Daiya Industry Co., Ltd. Since PGM is very light weight and flexible, it can be used as a wearable haptic suit. Because it does not inhibit human motion even if it is mounted on the body. Fig. 4.1 shows a schematic diagram of PGM. As shown in the figure, when air is injected into the inner tube, the PGM contracts and exerts a force in the direction of

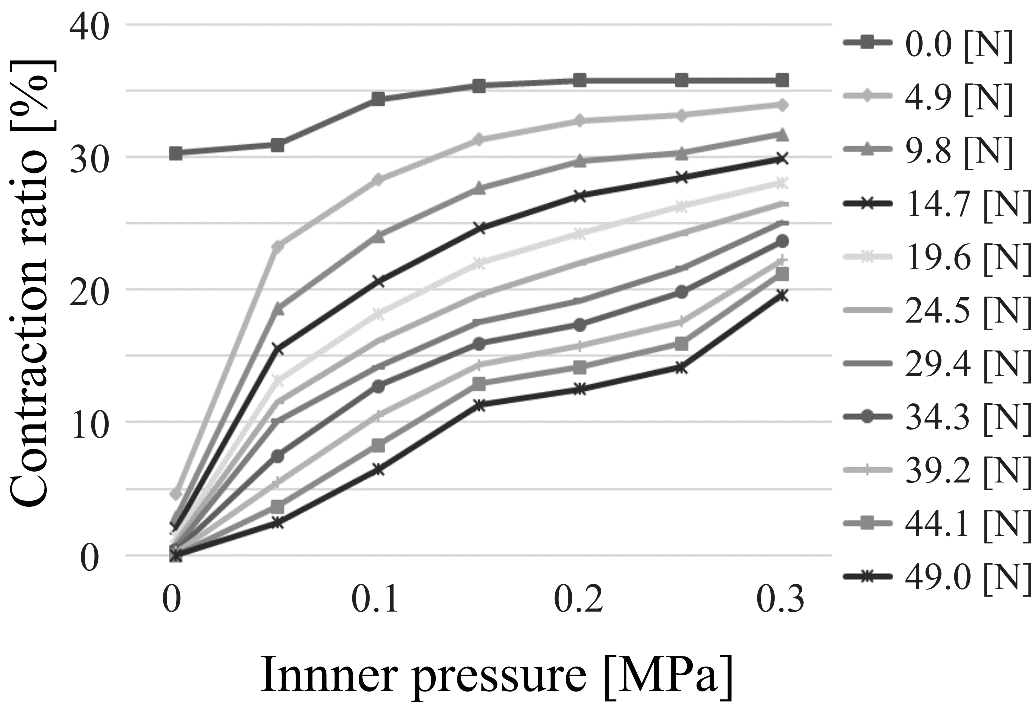


Fig. 4.2: Relationship between inner pressure and contraction ratio [9]

contraction, similar to human muscle. And, since PGM is low air pressure drive, it is driven by the air pressure of 0.1 - 0.3 MPa, and it demonstrates the force of 25 N at the largest, when the air of 0.1 MPa is injected.

Fig.4.2 shows the relationship between supplied air pressure and contraction rate investigated in [9]. In this experiment, one end of PGM was fixed, and the another end measured the shrinkage rate when various weights were attached. As can be seen from this figure, even if a weight of up to 49 N is attached in spite of low air pressure, contraction is possible.

Fig. 4.3: Haptic suit

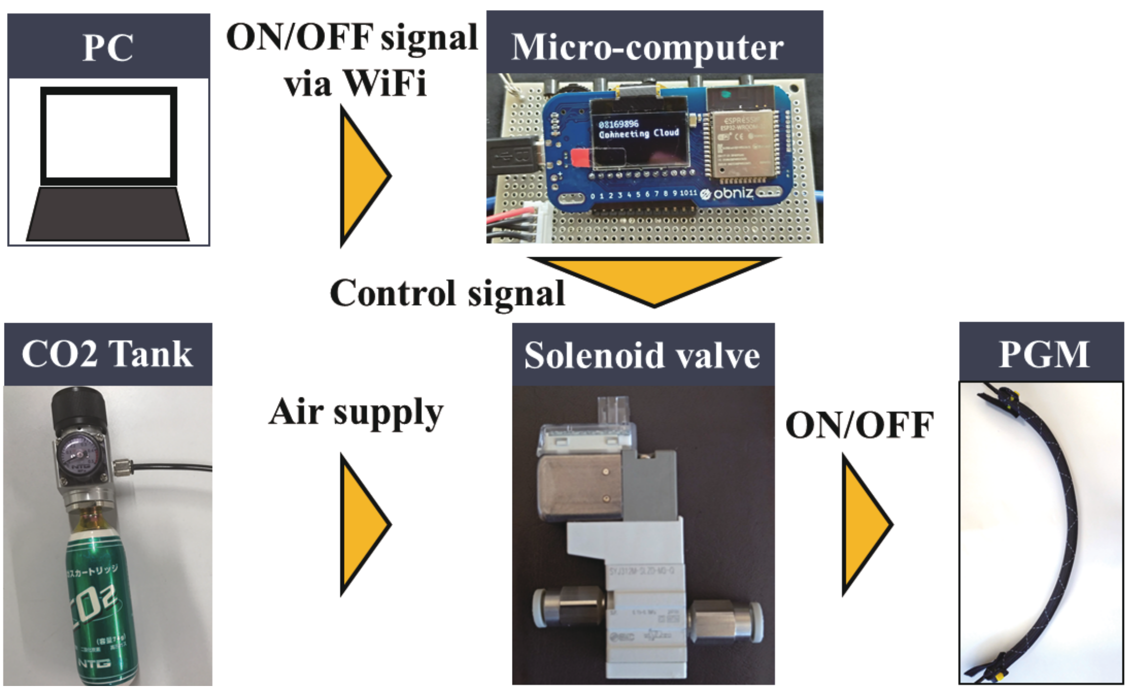


Fig. 4.4: PGM control system

4.2.3 Control System

The haptic suit is shown in Fig.4.3, and the overview of the control is shown in Fig.4.4. The PC sends an ON/OFF control signal to micro-computer via WiFi, and the PGM is driven by opening and closing the solenoid valve by micro-computer. CO2 is always supplied to the solenoid valve from the CO2 tank, and when the solenoid valve is opened, CO2 is sent to the PGM. On the right arm side of the suit, three PGMs are attached to apply the force in the flexion of the elbow, and three PGMs are also attached to apply the force in the extension of the elbow. Six solenoid valves are mounted on the back of the suit, and it is possible to control PGM in maximum 6 places. PGM can be controlled individually using different solenoid valves, and multiple PGMs can be controlled simultaneously using the same solenoid valve.

4.3 Experiment

The experiment was conducted by using the suit in 8 adults (Height: 172 $\pm$ 4.7 cm, Age: 0.99 $\pm$ 22.6 years). The objective of this experiment is investigation about the subjective perceived weight is changed by the suit.

A overview of the experiment is shown in Fig. 4.5. The subject hold a weight as a reference weight, then the subjects are asked how much the subjective perceived weight is changed by driving the PGM in suit. The subjects hold the weight with their elbows flexed 90 degrees. The PGM is attached to the front and back of the elbow, and the 4 stimuli are applied randomly. The 4 stimuli are the flexion force by using 1 PGM, flexion force by using 3 PGMs, extension force by using 1 PGM, and extension force by using 3 PGMs. The each stimulus are applied 3 seconds. The magnitude estimation method is used to answer how much the perceived weight changes with compare to the standard weight. Each stimulus is given 5 times, and the standard weights are applied

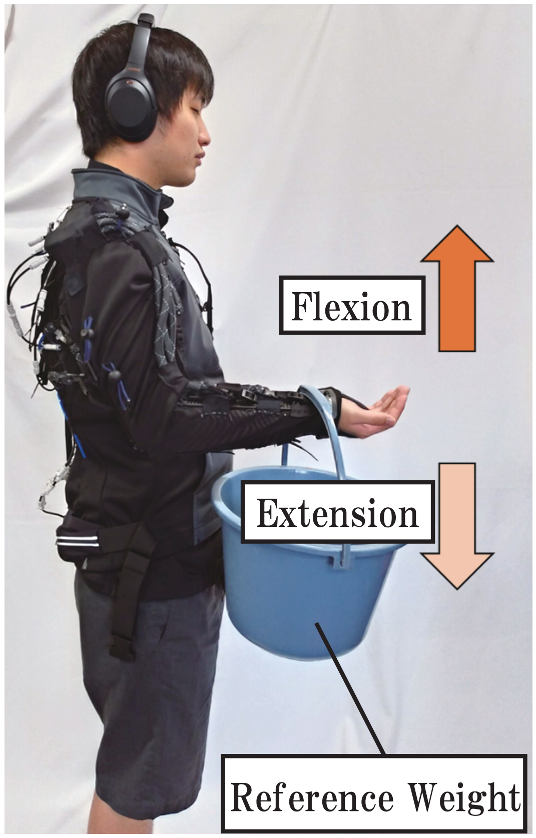


Fig. 4.5: Experimental overview

for each trial.

4.4 Result and Discussion

The experimental results are shown in Fig.4.6. In the flexion, the subjective perceived weight was reduced by 11% for PGMx1 and 19% for PGMx3. In the extension, the subjective perceived weight was increased by 8% for PGMx1 and 14% for PGMx3 was obtained. From this result, it was proven that the perceived weight was changed by contracting the PGM so as to act in the flexion and extension of the joint. ANOVA and multiple test showed significant differences in each experimental condition. That is to say, it was proven that the perceived weight was enhanced by changing the place

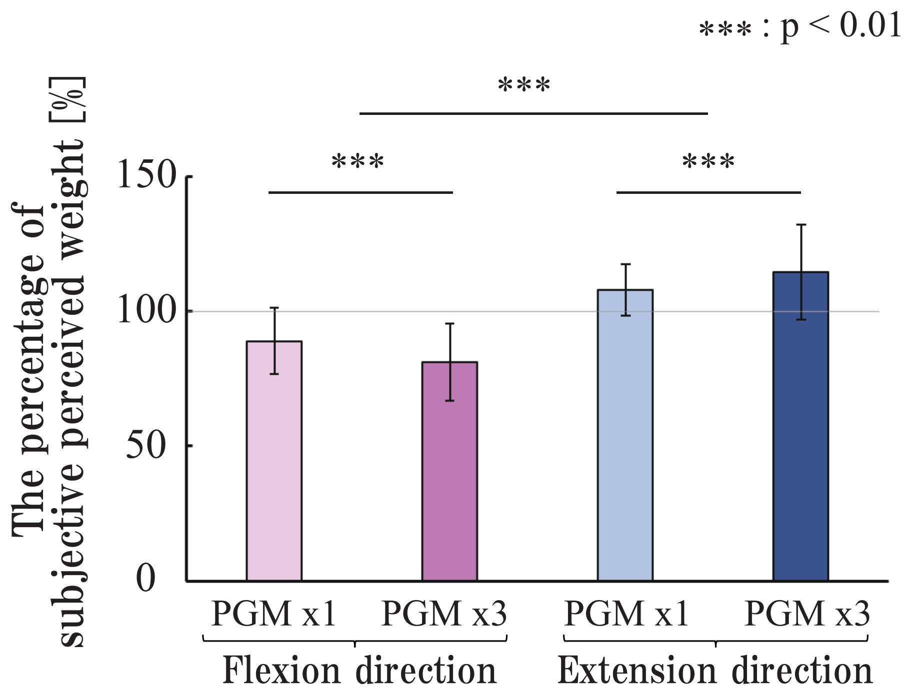


Fig. 4.6: Experimental result

of PGM. And the intensity of the perceived force is changed by the number of PGM. However, the rate of increase or decrease does not follow linearly with the number of PGM. Also, depending on the relationship between body size and suit size, PGM may not work well because of the tension of PGM. It is important to keep the tension firmly applied.

4.5 Concluding Remarks

In this chapter, the haptic suit which changed the subjective perceived weight of the human was developed. As a result of the experiment, significant increase and decrease of subjective feeling of weight were observed, and the result of changing the feeling of weight by the suit was obtained. The application by combining with the VR environment will be carried out in future.

Chapter 5

Conclusion

This dissertation outlined the prediction of perceived force from muscle activity during steering wheel operation. The validity of this model were examined through experiment of the comparison between predicted perceived force and measured perceived force. And also, the postural dependent force perceptual bias was investigated from the psychophysical experiment. The results of experiment were used for psychophysical experiment simulation by using perceived force prediction model and compared with simulation results. Development of haptic suit by using the knowledge of force perception was also outlined.

In Chapter 2, a model for predicting the perceived force during steering operation from muscle activity was proposed. This model is based on the Weber-Fechner law. This law states that perceptual intensity is proportional to the logarithm of the stimulus. In the model, the perceptual rate can be calculated directly from the intensity of muscle activity. The muscle activity was estimated by using 3D musculoskeletal model simulation. The commercially available vehicle's perceived force is estimated by using this model and compared with the measured perceived force to verify the accuracy of the model . The comparison result showed that the mean of the absolute error is 1.78N for the experiments conducted on four different vehicles.

In Chapter 3, the postural dependent force perceptual bias was investigated using the psychophsyical experiment. In this experiment, the force perceptual bias was investigated using the stair case method, and the experimental result was statistically analyzed. The result showed that the significant force perceptual bias was generated by the posture. And, the postural data was measured, then muscle activity was estimated by using 3D musculoskeltal model simulation with experimental data. The result was indicated that the muscle activity is changed due to the changing the posture, and that it affects the force perception. In addition, the psychophysical experiment simulation was conducted using perceived force prediction model and these results. A significant correlation of $r = 0.56$ was obtained between the experimented and predicted perceptual biases.

In Chapter 4, the haptic suit which changed the force perception using assist and resist to the muscle by using artificial muscle was developed. The suit has three artificial muscles attached to the front and back of the elbow joint, and can assist and resist the movement of the joint. The force perception is changed due to affect the intensity of muscle activity by using assist and resist force from artificial muscle. To investigate the changing force perception, psychophysical experiment was conducted. The result showed that the force perception was significantly changed by artificial muscle force.

In recent years, however, it has been reported that afferent signals from muscle spindles and skin receptors in the periphery are also important factors in determining sense of force/heaviness [1, 58, 59]. Although it has been confirmed that the sense of effort can be used for judging force/heaviness, an influential current hypothesis predicts that judgments of force/heaviness are based not only on sense of effort but also on feedback of afferent signals returning from the periphery [60]. Monjo et al. propose that humans do not perceive signals of only efferent or afferent signals as sense of effort but can perceive effort by changes in weight between both signals according to the experimental conditions [61]. The present experiment did not include conditions such as paralysis of muscle spindles. However, as Proske et al. report, it is necessary to provide participants with proper instructions when examining either efferent or afferent signals alone [1]. Since the prediction is carried out only by the muscle activity interpreted as the efferent signal, the afferent signals, such as sensing information from the muscle spindle and cutaneous sensation, which can be considered afferent feedback, appear to affect the prediction accuracy.

Additionally, although the range of steering reaction force is the same in the estimation model, the model was based on psychophysical experiments using both hands. Therefore, the current model cannot be completely applied in this case.

The accuracy of predicting perceptual bias depends on the accuracy of estimating the muscle activity using the musculoskeletal model. In this estimation, muscle co-contraction is neglected in the estimation of muscle activity using our method. Humans are known to perform stable movements by increasing joint stiffness through muscle co-contraction [51–53]. Therefore, it is important to consider muscle co-contraction when estimating muscle activity, to improve estimation accuracy. Additionally, Osu et al. report that muscle co-contraction decreases as humans become accustomed to motor tasks [54]. In other words, it is possible to improve accuracy by reducing the effect of co-contraction by setting experimental conditions under which co-contraction does not occur, or by selecting subjects who are familiar with such motor tasks.

In haptic suits, there were also the results that the force perception did not change. This is because that the attachment position of the artificial muscle dose not much the body size of the subject. Therefore, it is necessary to calibrate the optimum attachment position for each subject to apply the tension on the joints precisely.

In recent years, the haptic device is remarkable in the field of Virtual reality(VR). This is because it is possible to produce a more realistic by properly acting on tactile feeling as well as visual. In the future, this suit will be developed as a force feedback suit which can perceive the force in VR environment.

Publications concerning this dissertation are listed in the bibliography [18, 30, 62–65].

Bibliography

[1] U. Proske and T. Allen, "The neural basis of the senses of effort, force and heaviness.," *Experimental Brain Research*, vol. 237, pp. 589–599, 2019.

[2] J. De Camp, "The influence of color on apparent weight. a preliminary study," *Journal of Experimental Psychology*, vol. 2, no. 8, pp. 347–370, 1917.

[3] J. Flanagan, A. Wing, S. Allison, and A. Spenceley, "Effects of surface texture on weight perception when lifting objects with a precision grip," *Perception & Psychophysics*, pp. 282–290, 1995.

[4] J. S. Holmin and J. F. Norman, "Aging and weight-ratio perception," in *PloS one*, 2012.

[5] S. Gandevia and D. McCloskey, "Sensations of heaviness," *Brain*, vol. 100, no. 2, pp. 345–354, 1977.

[6] M. Joseph, "Muscle fatigue degrades force sense at the ankle joint," *International Journal of Industrial Ergonomics*, vol. 24, pp. 223–233, 1999.

[7] V. Nicolas and B. Matthieu, "Muscular fatigue and its effects on weight perception," *Gait & Posture*, vol. 28, pp. 521–524, 2008.

[8] T. Sakajiri, Y. Tanaka, and A. Sano, "Relation between gravitational and arm-movement direction in the mechanism of perception in bimanual steering.," *Experimental Brain Research*, vol. 231, pp. 129–138, 2013.

[9] K. Ogawa, C. Thakur, T. Ikeda, T. Tsuji, and Y. Kurita, "Development of a pneumatic artificial muscle driven by low pressure and its application to the unplugged powered suit," *Advanced Robotics*, vol. 31, no. 21, pp. 1135–1143, 2017.

[10] K. Takemura, N. Yamada, T. Niibe, A. Kishi, K. Nishikawa, T. Nouzawa, Y. Kurita, and T. Tsuji, "Kansei-related assessment and its application to a design for steering wheel operation characteristics in a subjective force perception space," *Transactions of the JSME (in Japanese)*, vol. 81, no. 822, pp. 14–00463–14–00463, 2015.

[11] P. Lindsay and D. Norman, eds., *Human Information Processing: An Introduction to Psychology.* Academic Press, 1977.

[12] S. Stevens, ed., *Psychophysics: Introduction to Its Perceptual, Neural, and Social Prospects.* John Wiley & Sons Inc, 1975.

[13] L. Jones, "Perception of force and weight: Theory and research.," *Psychol Bull*, vol. 100, pp. 29–42, 1986.

[14] A. Newberry, M. Griffin, and M. Dowson, "Driver perception of steering feel.," *J. Automobile Engineering*, vol. 221, pp. 405–415, 2007.

[15] S. Steven, "On the psychophysical law.," *Psychological Review*, vol. 64, no. 3, pp. 153–181, 1957.

[16] K. Takemura, N. Yamada, A. Kishi, K. Nishikawa, T. Nouzawa, Y. Kurita, and T. Tsuji, "A subjective force perception model of humans and its application to

a steering operation system of a vehicle.," in *IEEE International Conference of Systems, Man, and Cybernetics*, pp. 3675–3680, 2013.

[17] G. Fechner, ed., *Elements of Psychophysics. Translated by Helmut E.* Holt, Rinehart and Winston, U.S., 1966.

[18] Y. Kishishita, K. Takemura, N. Yamada, T. Hara, A. Kishi, K. Nishikawa, T. Nouzawa, T. Tsuji, and Y. Kurita, "Prediction of perceived steering wheel operation force by muscle activity.," *IEEE Transactions on Haptics*, vol. 11, pp. 590–598, 2018.

[19] V. van Polanen, R. Tibold, A. Nuruki, and M. Davare, "Visual delay affects force scaling and weight perception during object lifting in virtual reality," *Journal of Neurophysiology*, vol. 121, pp. 1398–1409, 2019.

[20] L. Jones and I. Hunter, "Effect of fatigue on force sensation.," *Experimental Neurology*, vol. 81, pp. 650–650, 1983.

[21] D. McCloskey, J. Brookhart, V. Mountcastle, V. Brooks, and S. Geiger, eds., *Corollary discharges: Motor commands and perception.* American Physiological Society, 1981.

[22] D. McCloskey, S. Gandevia, E. Potter, and J. Colebatch, "Muscle sense and effort: motor commands and judgments about muscular contractions.," *Advances in neurology*, vol. 39, pp. 151–167, 1983.

[23] E. Cafarelli and B. Bigland-Rilchie, "Sensation of static force in muscles of different length.," *Experimental Neurology*, vol. 65, pp. 511–525, 1979.

[24] H. Morree, C. Klein, and S. Marcora, "Perception of effort reflects central motor command during movement execution.," *Psychophysiology*, vol. 49, pp. 1242–1253, 2012.

[25] A. Zenner and A. Krüger, "Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality," *IEEE Transactions on Visualization and Computer Graphics*, vol. 23, pp. 1285–1294, April 2017.

[26] A. Zenner and A. Krüger, "Drag: on: A virtual reality controller providing haptic feedback based on drag and weight shift," in *CHI*, 2019.

[27] I. Choi, E. Ofek, H. Benko, M. Sinclair, and C. Holz, "Claw: A multifunctional handheld haptic controller for grasping, touching, and triggering in virtual reality," in *CHI*, 2018.

[28] I. Choi, E. W. Hawkes, D. L. Christensen, C. J. Ploch, and S. Follmer, "Wolverine: A wearable haptic interface for grasping in virtual reality," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 986–993, Oct 2016.

[29] Y. Konishi, N. Hanamitsu, K. Minamizawa, A. Sato, and T. Mizuguchi, "Synesthesia suit: the full body immersive experience," in *SIGGRAPH 2016 - ACM SIGGRAPH 2016 Posters*, Association for Computing Machinery, Inc, 7 2016.

[30] Y. Kishishita, A. V. Ramirez, S. Das, C. Thakur, Y. Yanase, and Y. Kurita, "Muscleblazer: a wearable laser tag module powered by pgm-induced force-feedback," in *Superhuman Sports Design Challenge*, 2018.

[31] L. L. Thurstone, "A law of comparative judgment," *Psychological Review*, vol. 34, no. 4, pp. 273–286, 1927.

[32] M. Kahrimanovic, W. Tiest, and A. Kappers, "The shapeweight illusion.," *In: EuroHaptics' 10 proceedings of the 2010 international conference on Haptics*, pp. 17–22, 2010.

[33] S. Delp, F. Anderson, A. Arnold, P. Loan, A. Habib, C. John, E. Guendelman, and D. Thelen, "Opensim: Opensource software to create and analyze dynamic simulations of movement.," *IEEE Transactions on Biomedical Engineering*, vol. 54, no. 11, pp. 1940–1950, 2007.

[34] D. Thelen, "Adjustment of muscle mechanics model parameters to simulate dynamic contractions in older adults.," *Journal of Biomechanical Engineering*, vol. 25, pp. 70–77, 2003.

[35] K. Holzbaur, W. Murray, and S. Delp, "A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control.," *Annals of Biomedical Engineering*, vol. 33, no. 6, pp. 829–840, 2005.

[36] F. Zajac, "Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control.," *Critical Reviews in Biomedical Engineering*, vol. 17, no. 4, pp. 359–411, 1989.

[37] R. Lieber and S. Bodine-Fowler, "Skeletal muscle mechanics: Implications for rehabilitation.," *Physical Therapy*, vol. 73, no. 12, pp. 844–856, 1993.

[38] C. Lanczos, ed., *The Variational Principles of Mechanics.* Dover Publications, NewYork, 1949.

[39] A. Pick and D. Cole, "Measurement of driver steering torque using electromyography.," *Journal of Dynamic Systems Measurement and Control*, vol. 128, pp. 960–968, 2006.

[40] L. Jones, "Perceptual constancy and the perceived magnitude of muscle forces.," *Experimental Brain Research*, vol. 151, pp. 197–203, 2003.

[41] B. Hood, "Gravity rules for 2- to 4-year olds?," *Cognitive Development*, vol. 10, pp. 577–598, 1995.

[42] J. Winter, T. Allen, and U. Proske, "Muscle spindle signals combine with the sense of effort to indicate limb position," *The Journal of Physiology*, vol. 568(Pt 3), pp. 1035–1046, 2005.

[43] H. Ross, E. Brodie, and A. Benson, "Mass-discrimination in weightlessness and readaptation to earth's gravity.," *Experimental Brain Research*, vol. 65, pp. 358–366, 1986.

[44] L. Young, C. Oman, C. Merfeld, D. Watt, S. Roy, C. DeLuca, D. Balkwill, J. Christie, N. Groleau, and D. Jackson, "Spatial orientation and posture during and following weightlessness: human experiments in spacelab life sciences 1.," *Journal of Vestibular Research*, vol. 3, pp. 231–239, 1993.

[45] S. Ss, "Problems and methods of psychophysics.," 1958.

[46] L. A. Jones and H. Z. Tan, "Application of psychophysical techniques to haptic research," *IEEE Transactions on Haptics*, vol. 6, pp. 268–284, 2013.

[47] A. S. Arnold, D. G. Thelen, M. H. Schwartz, F. C. Anderson, and S. L. Delp, "Muscular coordination of knee motion during the terminal-swing phase of normal gait.," *Journal of biomechanics*, vol. 40 15, pp. 3314–24, 2007.

[48] M. Q. Liu, F. C. Anderson, M. H. Schwartz, and S. L. Delp, "Muscle contributions to support and progression over a range of walking speeds.," *Journal of biomechanics*, vol. 41 15, pp. 3243–52, 2008.

[49] R. Neptune, S. Kautz, and F. Zajac, "Contributions of the individual ankle plantar flexors to support, forward progression and swing initiation during walking," *Journal of Biomechanics*, vol. 34, pp. 1387–1398, nov 2001.

[50] D. N. Reshef, Y. A. Reshef, H. K. Finucane, S. R. Grossman, G. McVean, P. J. Turnbaugh, E. S. Lander, M. Mitzenmacher, and P. C. Sabeti, "Detecting novel associations in large data sets," *Science*, vol. 334, no. 6062, pp. 1518–1524, 2011.

[51] N. Hogan, "Adaptive control of mechanical impedance by coactivation of antagonist muscles," *IEEE Transactions on Automatic Control*, pp. 681–690, 1984.

[52] R. Baratta, M. Solomonow, B. Zhou, D. Letson, and R. Chuinard, "Muscular coactivation : The role of the antagonist musculature in maintaining knee stability," *The American Journal of Sports Medicine*, vol. 16, pp. 113–122, 1988.

[53] P. Gribble, L. Mullin, N. Cothros, and A. Mattar, "Role of cocontraction in arm movement accuracy," *Journal of Neurophysiology*, vol. 89, no. 5, pp. 2396–2405, 2003.

[54] R. Osu, D. Franklin, H. Kato, H. Gomi, K. Domen, T. Yoshioka, and M. Kawato, "Short- and long-term changes in joint co-contraction associated with motor learning as revealed from surface emg," *Journal of Neurophysiology*, vol. 88, no. 2, pp. 991–1004, 2002.

[55] J. H. Mitchell, W. Haskell, P. G. Snell, and S. P. V. Camp, "Task force 8: classification of sports.," *Journal of the American College of Cardiology*, vol. 45 8, pp. 1364–7, 2005.

[56] Y. Tanaka, T. Sakajiri, and A. Sano, "A study on upper-limb motor control using mirror illusion in bimanual steering," in *Haptic Interaction*, pp. 13–15, Springer, 2015.

[57] M. Eksioglu and K. Kızılaslan, "Steering-wheel grip force characteristics of drivers as a function of gender, speed, and road condition," 2008.

[58] B. Luu, B. Day, J. Cole, and R. Fitzpatrick, "The fusimotor and reafferent origin of the sense of force and weight.," *Journal of Physiology*, vol. 589, no. 13, pp. 3135–3147, 2011.

[59] J. Brooks, T. Allen, and U. Proske, "The senses of force and heaviness at the human elbow joint," *Experimental Brain Research*, vol. 226, pp. 617–629, 2013.

[60] D. Phillips, P. Kosek, and A. Karduna, "Force perception at the shoulder after a unilateral suprascapular nerve block," *Experimental Brain Research*, 2019.

[61] F. Monjo, J. Shemmell, and N. Forestier, "The sensory origin of the sense of effort is context-dependent," *Experimental Brain Research*, vol. 236, pp. 1997–2008, 2018.

[62] Y. Kishishita, Y. Tanaka, and Y. Kurita, "Force perceptual bias caused by muscle activity in unimanual steering," *PLOS ONE*, vol. 14, pp. 1–14, 10 2019.

[63] Y. Kishishita, T. Tsuji, and Y. Kurita, "Computational prediction of subjective sense of force based on muscle activity estimation," in *Advances in Physical Ergonomics and Human Factors* (R. Goonetilleke and W. Karwowski, eds.), (Cham), pp. 687–694, Springer International Publishing, 2016.

[64] Y. Kishishita, K. Takemura, N. Yamada, T. Hara, A. Kishi, K. Nishikawa, T. Nouzawa, T. Tsuji, and Y. Kurita, "Computational prediction method of subjective sense of force during steering operation based on muscle activation," 2018.

[65] Y. Kishishita, S. Das, A. V. Ramirez, C. Thakur, R. Tadayon, and Y. Kurita, "Muscleblazer: Force-feedback suit for immersive experience," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1813–1818, March 2019.

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