F2006D107

STUDY ON ARM MANIPULABILITY EVALUATION TECHNIQUE FOR IMPROVEMENT OF OPERATION PERFORMANCE

[1]Yamada, Naoki*, [1]Masamori, Ichirou, [2]Tanaka, Yoshiyuki, [2]Tsuji, Toshio
[1]Mazda Motor Corporation, Japan, [2]Hiroshima University, Japan

KEYWORDS –Operation, door, manipulating force ellipsoid, musculoskeletal system

ABSTRACT – For improvement of the operation performance of vehicle operation equipment, it is important to consider mechanical characteristic adaptability of operation equipment with human musculoskeletal system at the early development stage.

We have developed the evaluation technique (analysis of manipulating force at hand) of mechanical characteristic musculoskeletal system by combination manipulating force ellipsoid, one of manipulability evaluation techniques of robotics, and the computer manikin. The musculoskeletal system has been modelled 3-dimensional 3-link 7-joint model considered characteristics of joints' torque.

Developed technique performed well in study on quantitative analysis considered characteristics of joint' torque, qualitative experiment of muscular load analysis at the operation of door and the operation performance development of a door system.

These results suggested potential of this technique for muscular load analysis and effectiveness of consideration of mechanical characteristic musculoskeletal system described by manipulating force ellipsoid (analysis of manipulating force at hand by this technique) for improvement on operation performance of operation equipment.

TECHNICAL PAPER

INTRODUCTION

The forecast technique of operation performance in the design early phase is desired to improve the adaptability of the vehicle operation equipment (door and the steering(4) wheel etc.) and human more efficiently though the evaluation by the subjectivity evaluation and the human measurement (electromyogram, motion capture) has been used up to now as an evaluation technique of operation performance. Recently, the computer manikin has been used by the design phase for the interior comfort assessments, but one to be predictable enough of mechanical characteristics of human musculoskeletal system is not found.

We have developed the evaluation technique (analysis of manipulating force at hand) of mechanical characteristic musculoskeletal system by combination manipulating force ellipsoid, one of manipulability evaluation techniques of robotics(1)-(3), and the computer manikin. The arm musculoskeletal system has been modelled 3-dimensional 3-link 7-joint model considered characteristics of joints' torque.

Developed technique was applied to the operation of several samples for a qualitative verification and the operation performance development of a new type rear-hinge door. These results suggested potential of this technique for muscular load analysis and effectiveness of consideration of mechanical characteristic musculoskeletal system described by manipulating force ellipsoid (analysis of manipulating force at hand by this technique) for improvement on operation performance of operation equipment.

BASIC CONSEPTS OF THE DEVELOPMENT

Basic concepts of the development is 2 points below,

・Presentation of result by figure assumed to be able to understand forecast result intuitively even if there is no expertise of human engineering

・Simple modelling that decreases calculation load, and enables narrowing necessary human characteristic data.

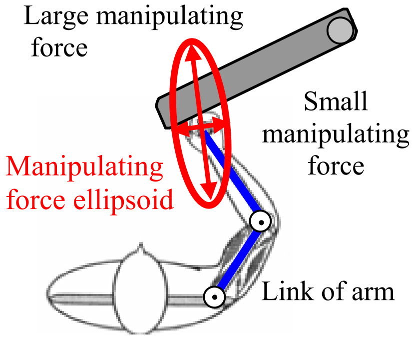


Fig.1 Manipulating Force Ellipsoid

We paid attention to one of the link analysis method of robotics (one of manipulability evaluation method; manipulating force ellipsoid) which was able to express mechanical characteristics as ellipsoid by analysis of manipulating force at hand (Fig.1).

ARM MANIPULABILITY EVALUATION TECHNIQUE

In the field of robotics, there have been several methods to evaluate the manipulating ability of multi-joint robotic mechanisms [(1)-(4)]. These previous methods, however, cannot consider any biological characteristics of human joint motor. This section proposes a new evaluation method inspired by human joint-torque characteristics.

Manipulating Force Ellipsoid Considered Human Joint-Torque

The musculoskeletal system of human can be modelled the multi-joint link structure. In general , using a force $\boldsymbol{f}$ exerted on the end-point of arm with n rotational joints in m dimensional task space the joint torque $\boldsymbol{\tau} \in \mathrm{R}^n$ is given by

$$\boldsymbol{\tau} = \boldsymbol{J}^T \boldsymbol{f} \tag{1}$$

where $\boldsymbol{J}(\boldsymbol{\theta}) \in \mathrm{R}^{m \times n}$ is the Jacobian matrix on the end-point position $\boldsymbol{x} \in \mathrm{R}^m$ with respect to $\boldsymbol{\theta} \in \mathrm{R}^n$. For consideration of human joint torque characteristics $\boldsymbol{\tau}$ is modelled as follows:

$$\boldsymbol{\tau} = \boldsymbol{T}(\boldsymbol{\theta})\,\boldsymbol{\alpha} \tag{2}$$

where $\boldsymbol{T}(\boldsymbol{\theta}) = \mathrm{diag.}\,(\tau_{1j}^{max}(\theta_1), \tau_{2j}^{max}(\theta_2), \cdots, \tau_{nj}^{max}(\theta_n))^T \in \mathrm{R}^{m \times n}$ ($j \in \{f,e\}$;the suffix f and e indicate the flexional direction and the extensional direction ,respectively) is a diagonal matrix of which the element is the absolute value of the maximum joint torque at the angle θ_i. The joint-torque activation level vector $\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \cdots, \alpha_n)^T \in \mathrm{R}^n$ $\alpha_i(|\alpha_i| \leqq 1)$ represents the ratio of i-th join-torque to the maximum torque under the maximum voluntary contraction (MVC) and its sign denotes the joint rotational direction (the flexional direction is defined as positive). Substituting (1) into (2), $\boldsymbol{\alpha}$ can be represented with $\boldsymbol{f}$ as follows:

$$\alpha = T(\theta)^{-1} J(\theta)^{T} f \tag{3}$$

A set of the force f generated by the muscles within $\|\alpha\| \leqq 1$ then makes an m dimensional ellipsoid presented by

$$\alpha^{T}\alpha = f^{T}(JT^{-1})(JT^{-1})^{T} f \leqq 1 \tag{4}$$

The manifold on f in (4) is manipulating force ellipsoid in reflected the characteristics of human joint-torque by the matrix $T(\theta)$ The principal axes of the ellipsoid can be obtained by a singular value decomposition of (JT^{-1}). The shape of this ellipsoid indicates a performance index in generating force according to the operational direction under the link posture θ. For example large operational force can be easily exerted in the major axis direction, while it is difficult toward the minor axis direction. This method was applied to the arm as the model of three links and seven rotational joints that consisted of three joints in shoulder, two joints in elbow and two in wrist.

Method of Joint-Torque Measurement

Experimental Apparatus

Fig.2 illustrates the experimental apparatus for investigating human joint-torque characteristics, which consists of the measurement part of joint-torque and electromyogram (EMG) signals, and the biofeedback display in order to monitor the muscle activation level during experiments. The EMG signals were measured from the agonists as shown in Table 1 with an amplifier and a set of disposable electrodes. The measured EMG signals were rectified and integrated with the data during the past 0.1 seconds, and then normalized value was utilized as the muscle contraction level in this paper.

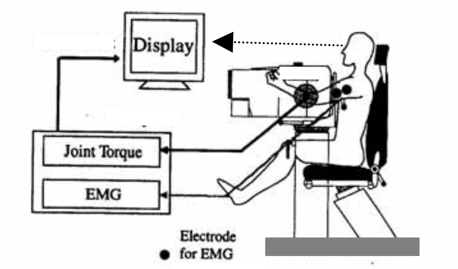


Fig.2 Joint-Torque Measurement

Experimental Method

In the experiments, a subject is instructed to generate his/her joint-torque by using agonist toward the specified rotational direction without co-contraction under the 40% muscle contraction level, while the subject can monitor the progress on the biofeedback display in front of him/her. Joint torques in each of uniarticular movements are measured twice for 10 seconds at the joint angle changed by $\pi/9$ [rad] around the middle of joint excursion. The measurement

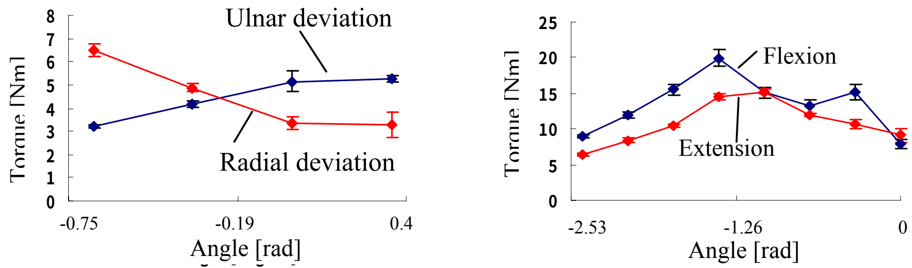
Table 1 Muscles for Uniarticular Movements

Joint	Motion	Muscle
Wrist	Flexion	Flexor Carpi Radialis
	Extension	Extensor Carpi Ulnaris
	Radial deviation	Flexor Carpi Radialis
	Ulnar deviation	Extensor Carpi Ulnaris
Elbow	Pronation	Pronator Teres
	Supination	Biceps Brachii
	Flexion	Biceps Brachii
	Extension	Triceps Brachii
Shoulder	Flexion	Deltoideus Anterior
	Extension	Latissimus Dorsi
	Adduction	Pectoralis Major
	Abduction	Deltoideus, Middle
	Internal rotation	Teres Major
	External rotation	Infraspinatus

experiments were carried out with the four male subjects under the conditions mentioned above.

Experimental Results

It has been clarified that each joint torque characteristic showed nonlinear features depended on joint angle and rotational direction and it has a different peak value with each joint. Fig.3 represents typical examples of the measured joint-torque a subject in the wrist radial deviation and ulnar deviation, the elbow flexion and extension. Almost the same characteristics were observed on other subjects and joints. Through observations of the experimental results, two tendencies of the joint-torque characteristics have been found in the uniarticular movements: (i) the joint-torque is almost proportional to the joint angle as in the wrist radial deviation and ulnar deviation. (ii) the joint-torque peaks at the neutral angle of range of joint motion as in the elbow flexion and extension.



(a) Wrist joint (b) Elbow joint

Fig.3 Examples of Joint-Torque Characteristics

<u>Quantitative Verification by Basic Experiment</u>

Experiment of Manipulating Force Measurement

The manipulating force exerted on the end-point of arm and the posture of arm was measured using the experiment system showed in Fig.4. This system consists of the manipulating force measurement part, posture measurement part and the display that feeds back the force value and direction exerted on the end-point of arm back to a subject in real time. For the manipulating force measurement part six-axis force sensor was used. For the posture measurement part a 3-dimensional motion capture system with stereo cameras was used.

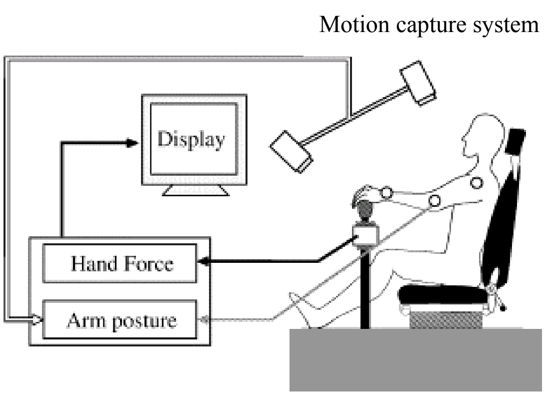


Fig.4 Experimental Apparatus for Measurement of Human Manipulating Force

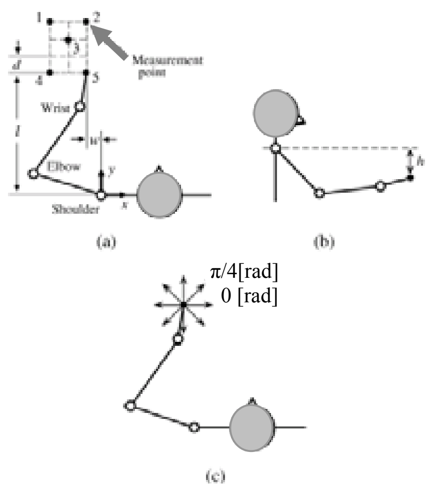


Fig.5 Experimental Condition for Measurement of Human Force

In the experiment, the subject sitting on the seat was directed to exert force by the maximum effort to the direction showed in the display for five seconds with the maintained posture that the left hand was affixed to the column stick in which the force sensor was installed (refer to Fig. 4). The measurement points are showed in Fig.5 (a) (b) (sign ●; total five points, where l = 350 [mm], w = h = 150 [mm] and d = 50[mm]). The directions of force exerted on the end-point of arm was assumed eight directions every $\pi/4$ [rad] on a 2-dimensional horizontal plane (showed in Fig.5 (c)). In the above-mentioned experimental conditions, the measurement experiment was carried out with four subjects (college students).

Verification

For verification of the proposal evaluation method the comparison of evaluation results with the above measurement experiment was carried out.

Manipulating force of arm at the measurement points in Fig.5 (a) (b) was evaluated by proposal methods with equation (4). Where $\boldsymbol{J}$ was calculated with measured posture by motion capture system and $\boldsymbol{T}^{-1}$ was calculated with $\tau_{ij}^{max}(\theta_i)$ obtained by conversion of measured joint-torque under the 40% muscle contraction level to estimated joint-torque under the 100% muscle contraction level.

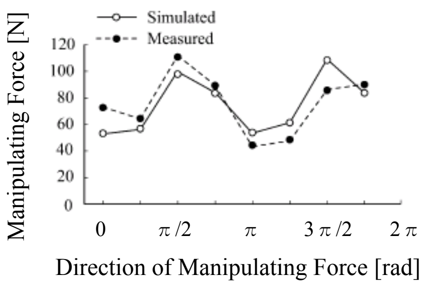


Fig.6 Comparison of Manipulating Force

Fig.6 shows one of comparison results of a subject at measurement point 2. Evaluated value and direction of manipulating force of arm by the proposal method is thus close to the results by measurement experiment with actual human. The similar tendency was able to be confirmed about the other measurement points and subjects.

Through basic experiment, the proposal method is verified quantitative evaluating the human manipulating force ability effectively.

Verification of Effectiveness in Actual Human Operation and Combination with Computer Manikin

In this paper, proposed method is verified its qualitative effectiveness for explanation of muscular load in actual operation in which arm posture change. Three type door operations "horizontal slide operation", "vertical operation" and "anterior-posterior operation" was took as example of actual operation. In "anterior-posterior operation" the forecast technique by combining the proposal method with the computer manikin was applied.

"Horizontal slide Operation"

As horizontal slide operation the experiment of opening operation outside a vehicle with a rear slide door was carried out (Fig.7). Fig.8 shows a mechanical characteristic of the door figured operation force-stroke characteristics (F-S characteristic). The measurement devices

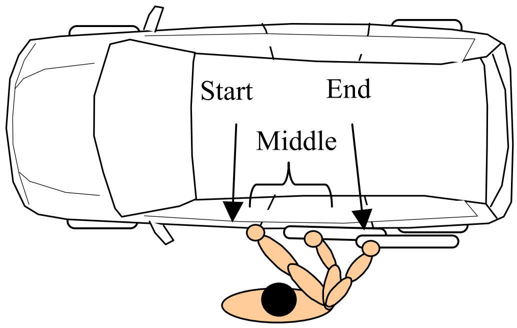


Fig.7 Operation of Slide Door

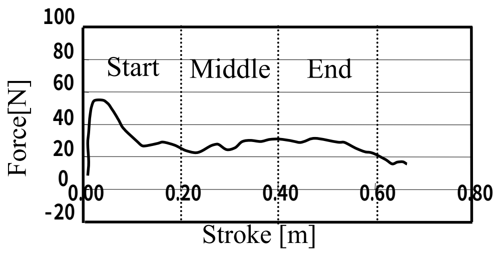


Fig.8 Force-Stroke Characteristics

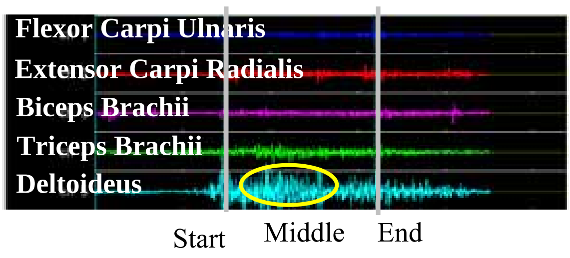


Fig.9 EMG during Slide Door Operation

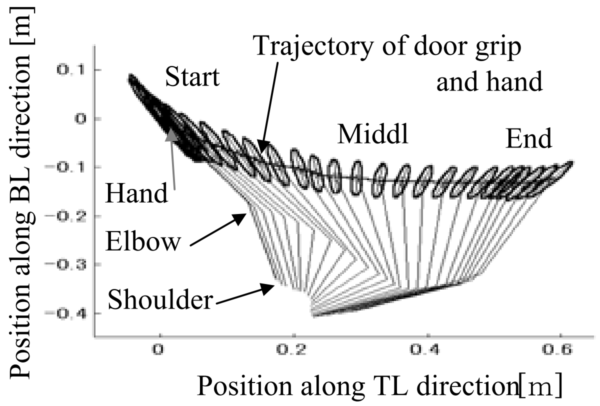


Fig.10 Manipulating Force Ellipsoid and Trajectory of Door Grip

of EMG for muscular load analysis and the 3-dimentional optical motion capture system for arm posture analysis were used in the experiment of door operation for three subjects. Fig.9 shows the example of the EMG. Fig.10 shows manipulating force ellipsoids calculated from the motion capture data of arm postures under operation, arm postures and the trajectory of the door grip (the end-point of arm). T is assumed to be a unit matrix in this paper because of qualitative validation of effectiveness.

The mechanical operating force of the door shows the peak immediately after operation start and decreases almost 1/2 or less while from middle to end of operation (Fig.8). On the other hand, the muscular load at Deltoideus shows high activity in the middle operation area (Fig.9) while operating force of the door shows lower value.

It is thought that a mechanical characteristic of the arm "Easiness of exertion of manipulating force" influences in this phenomenon. In the middle operation area major axis of manipulating force ellipsoid, which describes "Easiness of exertion of manipulating force" as its major axis, crosses the direction of operation trajectory. It can be understood that in this area "Difficulty of exertion of manipulating force" to the direction of operation trajectory related to the posture of arm influences in the increase of muscular load.

"Vertical Operation"

As vertical operation the experiment of closing operation with the lift gate was carried out (Fig.11). The similar tendency of horizontal slide operation was confirmed about vertical operation. Fig.12 shows muscular load during lift gate operation. In hold area muscular load

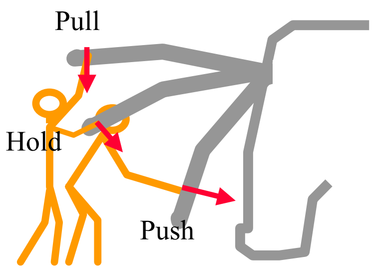


Fig.11 Operation of Lift Gate

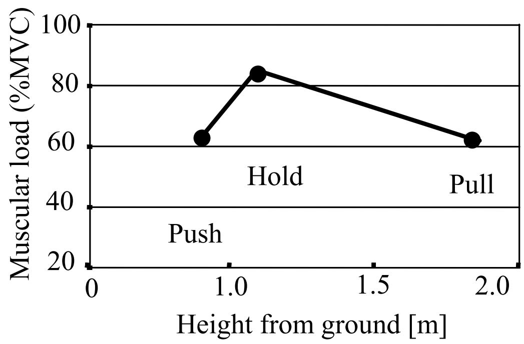


Fig.12 Muscular Load during Lift Gate Operation

shows peak. Fig.13 shows manipulating force ellipsoids. It is also thought that a mechanical characteristic of the arm "Easiness of exertion of manipulating force" influences in this phenomenon. In the hold area major axis of manipulating force ellipsoid, which describes "Easiness of exertion of manipulating force" as its major axis, crosses the direction of operation. It can be understood that in this area "Difficulty of exertion of manipulating force" to the direction of operation trajectory related to the posture of arm influences in the increase of muscular load. Through the actual operation experiments, the proposal method is verified qualitative effectiveness for the explanation and the estimation of muscular load influenced by the mechanical characteristics of human arm.

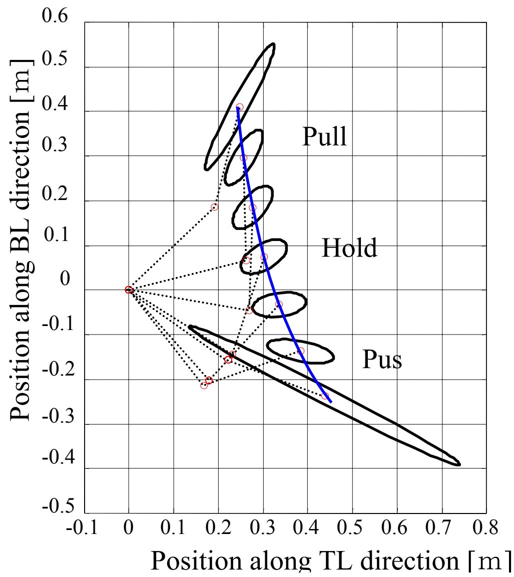


Fig.13 Manipulating Force Ellipsoid during Lift Gate Operation

"Anterior-posterior Operation" applied Combination with Computer Manikin

This section describes the establishment of the forecast technique by combining the proposal method with the computer manikin and an application example to "anterior-posterior operation".

Fig.14 shows the conceptual diagram of the forecast technique. Manipulability forecast technique obtains dimensions and joint-angles of upper limbs from computer manikin, which simulates posture at operation, evaluates manipulability and displays manipulating force ellipsoid with the manikin and CAD drawing.

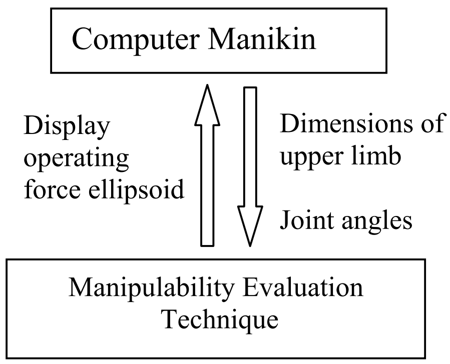
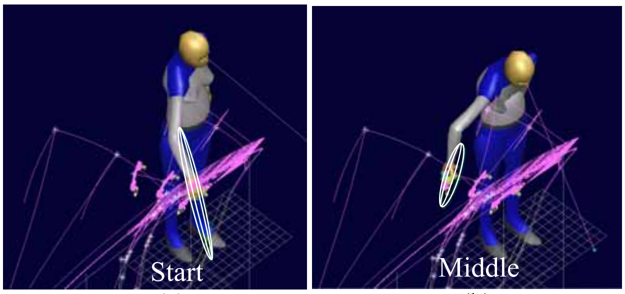


Fig.14 Forecast Technique of Manipulability



(a) (b)

Fig.15 Manipulating Force Ellipsoid
(Front Hinge Type Door)

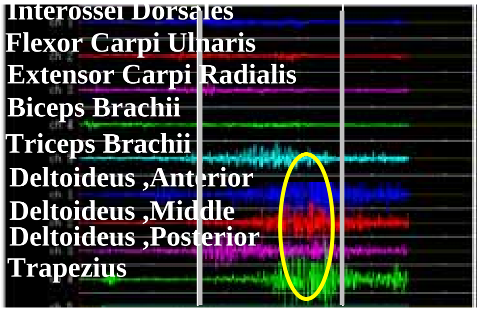


Fig.16 EMG(Front Hinge Type Door)

As anterior-posterior operation the experiment of opening operation outside a vehicle with a typical front hinge type door was carried out. Fig.15 shows manipulating force ellipsoids combined computer manikin with CAD drawing. The similar tendency of horizontal slide operation or vertical operation was confirmed about anterior-posterior operation. Fig.16 shows the example of the EMG. The muscular loads at Deltoideus and Trapezius show high activity in the middle operation area.

In the middle operation area major axis of manipulating force ellipsoid, which describes "Easiness of exertion of manipulating force" as its major axis, crosses the direction of operation trajectory. It can be understood that in this area "Difficulty of exertion of manipulating force" to the direction of operation trajectory related to the posture of arm influences in the increase of muscular load.

"Easiness of exertion of manipulating force" estimated by the proposal manipulability forecast technique is verified qualitative effectiveness for the explanation and the estimation of muscular load influenced by the mechanical characteristics of human arm.

APPLICATION TO IMPROVEMENT OF DOOR OPERATION PERFORMANCE

Application of the Forecast Technique

In this section a example of application of the proposal forecast technique to closing operation of new type rear hinge door inside the vehicle are introduced. The target of the door operation force characteristics was derived effectively for decrease of muscular load by this technique from the viewpoint of a mechanical characteristic of human arm.

Layout Design of Inner Grip

First Layout design of inner grip was focused because of the importance from the viewpoint of force transferring parts arm to door movement by connecting arm and door. Fig.17 shows manipulating force ellipsoids at 0, $2\pi/9$, $4\pi/9$[rad] of door opening degree. It can be understood that at each opening degree "Difficulty of exertion of manipulating force" to the direction of operation trajectory related to the posture of arm influences in the increase of muscular load. For decrease of muscular load it is a effective layout design of inner grip far from hinge center, but it means the deterioration of reachability. The idea of use of door moving element of major axis of manipulating force ellipsoid, which presents direction of “Easiness of exertion of manipulating force”, solved this dilemma (Fig.18). Vertical type grip which enables use of “Easiness of exertion of manipulating force” direction because of its

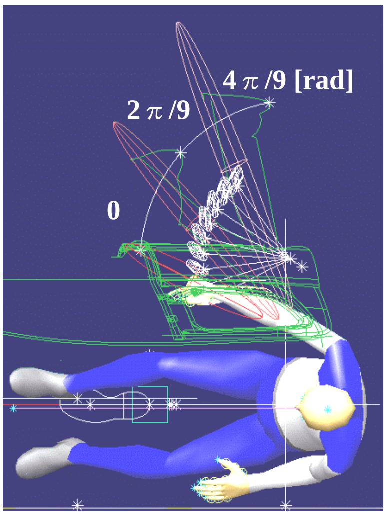
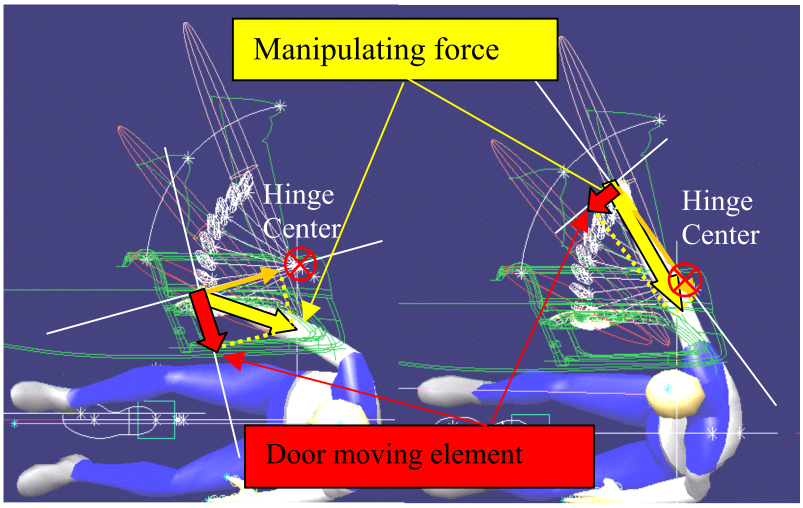


Fig.17 Manipulating Force Ellipsoid (New Type Rear Hinge Door)



Easy to operate (a) 0 [rad]]

Difficult to operate (b) 4 π /9 [rad]

Fig.18 Element of Manipulating Force

easiness to grasp and draw toward major axis of manipulating force ellipsoid at all door opening degree was designed in position prioritized reachability.

Door Operating Force Characteristics

Fig.18 also shows door moving element of major axis of manipulating force ellipsoid is small at 4 π /9[rad] of door opening degree. So the door operating force characteristics is targeted to decrease of muscular load effectively as Fig.19. To realize this characteristics the part (check link) for controlling door operation force was given operating force sassiest characteristics at 4 π /9[rad] of door opening degree by changing shape of plane cam for this new type rear hinge door.

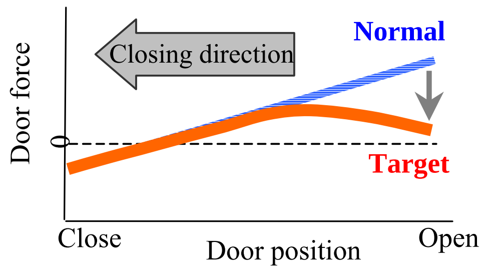


Fig.19 Target of Door Force

Experimental Verification

To confirm effectiveness of the design considered "Easiness of exertion of manipulating force" by proposal forecast technique for reduction of the muscular load, the experimental verification was carried out. Fig.20 shows the appearance of the experiment on the door operation. EMG and direction of manipulating force on the inner grip with pressure distribution sensor attached the hand of the subject (average Female of Japanese:JF50%ile). Fig.21 is shows the direction of manipulating forcer calculated by the pressure distribution. In beginning the door

Fig.20 Door Operation Test

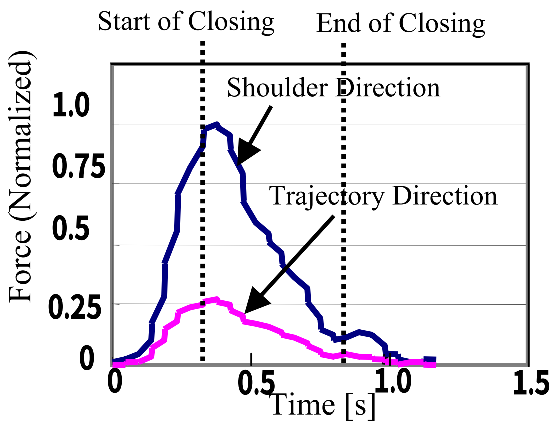


Fig.21 Analysis of Operating Force Direction

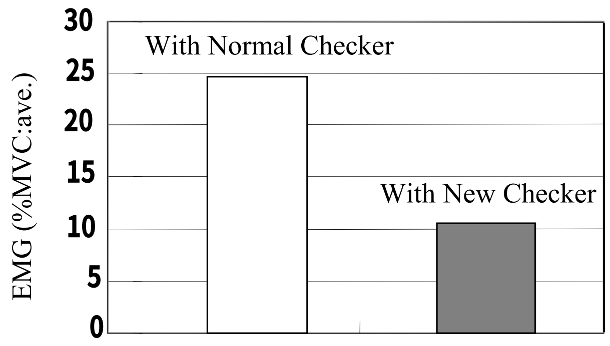


Fig.22 EMG Comparison

closing where operating force is necessary, it is understood that force exerted on the direction of the shoulder, which is direction of "Easy to exert manipulating force".

Fig.22 shows the muscular load comparison of the door with the improved check link to which targeted characteristic was installed and the door with usual one in beginning the door closing. It is understood to have reduced the muscular load by half in the improved door.

SUMMARY

We have developed the evaluation technique (analysis of manipulating force at hand) of mechanical characteristic musculoskeletal system by combination manipulating force ellipsoid, one of manipulability evaluation techniques of robotics, and the computer manikin. The musculoskeletal system has been modeled 3-dimensional 3-link 7-joint model considered characteristics of joints' torque.

It has been clarified that the measured each joint torque characteristic showed nonlinear features depended on joint angle and rotational direction and it has a different peak value with each joint. And two tendencies of the joint-torque characteristics have been found in the uniarticular movements: (i) The joint-torque is almost proportional to the joint angle as in the wrist radial deviation and ulnar deviation. (ii) The joint-torque peaks at the neutral angle of range of joint motion as in the elbow flexion and extension. Through basic experiment, the proposal evaluation method inspired by human joint-torque characteristics is verified quantitative evaluating the human manipulating force ability effectively.

Developed technique performed well in qualitative experiment of muscular load analysis at the operation of door and the operation performance development of a door system.

These results suggested potential of this technique for muscular load analysis and effectiveness of consideration of mechanical characteristic musculoskeletal system described by manipulating force ellipsoid (analysis of manipulating force at hand by this technique) for improvement on operation performance of operation equipment.

Acknowledgements

The authors would like to thank Prof. A. Otsuka of Prefectural University of Hiroshima and all concerned in this research.

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