Analysis of the Interaction Torque on the Arm Based on Via-Point Movement

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ABSTRACT

To produce a desired movement, the human motor control system must regular the interaction torque generated owing to the multi-joint structure of the body. In this study, the trajectories of human movements were evaluated considering the interaction torque generated through the elbow and shoulder joints. Measurement experiments were conducted, in which the participants performed movements corresponding to a three-point task, and the results indicated that the interaction torque is correlated with certain characteristics of the trajectories of the arm movements. Moreover, the contribution of the interaction torque in realizing the task differs in the cases of dominant and non-dominant hands. In addition, through a simulation, the interaction torque of simulated trajectories was modulated to examine the corresponding effect on the arm movements. For a point-to-point movement, certain characteristics of the actual movements were reproduced in the simulated trajectories. However, for a three-point movement, the characteristics of the simulated trajectories were only partially similar to those of the measured trajectories. The findings indicate that the interaction torque notably influences the motor control, and the tuning of the interaction torque is more complex than the other criteria of motor control.

KEYWORDS: *Motor Control, Arm Movement, Via-Point Movement, Interaction Torque, Hand Laterality, Human Interface*

1.0 INTRODUCTION

The human body consists of multi-joint structures, and a human can perform a desired motor task by adequately controlling many joints simultaneously. A human can produce a simple movement, such as moving his/her hand from a start position to a target position, with little difficulty and effort. However, the equations of motion regarding multi-joint structures are highly complex, and to produce adequate joint torque, motor commands, and muscle tensions to realize a movement, the motor control system of a human must solve these complex equations. Many researchers have predicted the existence of inner models in the cerebellum, which solve such complex equations (Wolpert et al., 1995; Wolpert et al., 1998; Frith et al., 2000).

Furthermore, several researchers have examined the types of acquired abilities and the criteria that are employed by the inner models of the motor control system. In this regard, an approach is to identify the difference in the movements depending on the

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experimental conditions. For example, when realizing a reaching movement with the upper arm, the trajectories of the movement for the dominant and non-dominant arms are notably different. In the existing studies, it was reported that such a difference in the movements can be attributed to the difference in the ability of the motor control system with respect to the dominant and non-dominant hands. This aspect does not correspond to the inferiority of the non-dominant hand but the ability of the inner model (Sainburg & Kalakanis, 2000; Bagesteiro & Sainburg, 2002; Bagesteiro & Sainburg, 2003). Specifically, the interaction torque was considered to be the main cause for this difference, and it was observed that the joint torque in the motor control system of the dominant hand was more efficient than that of the non-dominant hand.

In general, the interaction torque is generated through the driving of other joints in a multi-joint configuration. When an arm is considered as a two-joint manipulator (shoulder and elbow), the elbow joint is expected to move even when only the shoulder joint torque is exerted voluntarily. Similarly, the shoulder joint is expected to move even when only the elbow joint torque is exerted. Gribble & Ostry (1999) examined a single-joint movement involving an elbow and a shoulder joint, and measured the activity of the muscles involved in the movements. Notably, the authors demonstrated the activity of the muscles that drove and restricted the joint and explained that such activity is necessary to cancel the effect of the interaction torque generated owing to the moving joint and to relieve the other joint.

The motor control system, composed of the inner models, must take into account the effect of the interaction torque to adeptly control the human body, which involves a multi-joint structure (Gribble & Ostry, 1999; Yamasaki et al., 2008). Certain reports indicated that patients with cerebellar ataxia and blocked autoreceptive afferent pathways could not consider the interaction torque and thus could not capture a target in reaching tasks (Bastian et al., 1996; Messier et al., 2003).

Although the effect of the interaction torque must be critically examined to gain insight into the motor control system, the existing work concerning the effect remains limited. There, in this study, the effect of the interaction torque of the elbow and shoulder joints in a horizontal plane was investigated by conducting measurement and simulation experiments. In the measurement experiment, a via-point movement was adopted, which is a more difficult motor task than a reaching movement, which was primarily adopted in the existing studies. In the simulation experiment, the trajectories of an upper limb movement were computed under modulated motor commands to vary the effect of the interaction torque.

This research was approved by the ethics committee of Okayama Prefectural University.

2.0 INTERACTION TORQUE

When an upper limb is regarded as a two-joint manipulator, the equation of motion for the upper limb in the horizontal plane can be expressed as

$$\begin{aligned} \mathrm{MUS}_1 &= (I_1 + I_2 + 2m_2 l_1 r_2 \cos\theta_2)\ddot{\theta}_1 + (I_2 + m_2 l_1 r_2 \cos\theta_2)\ddot{\theta}_2 \\ &\quad - m_2 l_1 r_2 \big(2\dot{\theta}_1 + \dot{\theta}_2\big)\sin\theta_2 + b_{11}\dot{\theta}_1 + b_{12}\dot{\theta}_2 \\ \mathrm{MUS}_2 &= I_2\ddot{\theta}_2 + (I_2 + m_2 l_1 r_2 \cos\theta_2)\ddot{\theta}_1 + m_2 l_1 r_2 \dot{\theta}_1^2 \sin\theta_2 + b_{21}\dot{\theta}_1 + b_{22}\dot{\theta}_2 \end{aligned} \tag{1}$$

where subscripts 1 and 2 correspond to the parameters related to the shoulder joint and upper arm and those related to the elbow joint and forearm, respectively. MUS denotes the muscular torque of the joint, I denotes the moment of inertia around the arm joint, l denotes the length of the arm, r denotes the length from the proximal joint to the center of gravity of the arm, m denotes the mass of the arm, b denotes the viscosity of the joint, and θ denotes the joint angle.

As shown in Equation (1), the muscular torque exerted by each joint is affected not only by the movement of the link acting directly on the joint, but also by the other joint. Herein, the torque used in the movement of a link directly connected to the joint and that of the link not directly connected to the joint are denoted as the net torque (NET) and interaction torque (INT), respectively. The NET and INT of the shoulder and elbow joints can be expressed as in Equation (2). As an example, the muscle, net and interaction torque of the shoulder and elbow joints in the movement, which corresponds to the movement analyzed in section **4.1**, between two-points are shown in Figure 1.

$$\begin{aligned}
\mathrm{NET}_1 &= (I_1 + I_2 + 2m_2 l_1 r_2 \cos\theta_2)\ddot{\theta}_1 + b_{11}\dot{\theta}_1 \\
\mathrm{INT}_1 &= -(I_2 + m_2 l_1 r_2 \cos\theta_2)\ddot{\theta}_2 + m_2 l_1 r_2 (2\dot{\theta}_1 + \dot{\theta}_2)\sin\theta_2 - b_{12}\dot{\theta}_2 \\
\mathrm{NET}_2 &= I_2\ddot{\theta}_2 + b_{22}\dot{\theta}_2 \\
\mathrm{INT}_2 &= -(I_2 + m_2 l_1 r_2 \cos\theta_2)\ddot{\theta}_1 - m_2 l_1 r_2 \dot{\theta}_1^2 \sin\theta_2 - b_{21}\dot{\theta}_1 \\
\mathrm{MUS}_{1,2} &= \mathrm{NET}_{1,2} - \mathrm{INT}_{1,2}
\end{aligned} \tag{2}$$

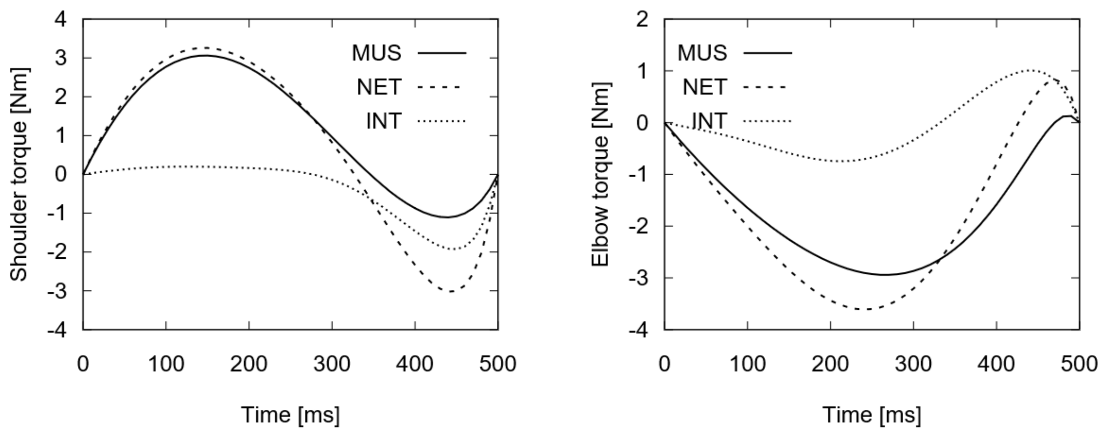

Figure 1 An example of the relation of joint torques. The muscle (MUS), net (NET) and interaction (INT) torque of the shoulder and elbow joints in the point-to-point movement.

Based on Equation (2), the efficiency of the joint torque in a movement can be evaluated by examining whether the interaction torque hinders or facilitates the realization of a movement. Hirashima et al. (2003) proposed the index of coordination between the interaction torque and muscle torque (IOCIM) to quantitatively evaluate the efficiency of the joint torque. The IOCIM can be defined as in Equation (3).

$$\mathrm{IOCIM} = \frac{\int_0^T \mathrm{IS}(t)dt}{\int_0^T \mathrm{MS}(t)dt}$$

$$\mathrm{IS}(t) = \begin{cases} -|\mathrm{INT}(t)| & \text{if } \mathrm{INT}(t)\cdot\mathrm{MUS}(t) < 0 \\ +|\mathrm{INT}(t)| & \text{if } \mathrm{INT}(t)\cdot\mathrm{MUS}(t) \geq 0 \end{cases}$$
$$\mathrm{MS}(t) = +|\mathrm{MUS}(t)| \tag{3}$$

where T denotes the movement duration. $\mathrm{IS}(t)$ in Equation (3) is characterized by the equality of the signs of the interaction torque and muscle torque. In general, the value of the INT is smaller (in certain instances it is a negative value) and larger when the INT impedes or facilitates the movement, respectively. The IOCIM is defined to evaluate the contribution of the INT over the entire movement.

3.0 MEASUREMENT EXPERIMENT

3.1 Conditions

The experimental task corresponded to the realization of a reaching movement between two points via one target in a horizontal plane. Five healthy right-handed students (4 male and 1 female students) participated in the experiment. The participants were instructed to hold the stylus of a measurement device (Touch X, 3D Systems) with their right or left hand, and to begin a movement at the start point, pass through the via-point, and reach the end point as rapidly and precisely as possible.

To define the coordinate system for the workspace, the intersection of the working horizontal plane and participant's midline was defined as the origin $(0, 0)$. The directions to the right and front of the participant were defined as the positive x- and y-axes, respectively. Three points were assigned as the start, via-, and end points as follows A $(-0.1, 0.3)$ [m], B $(0.0, 0.39)$ [m], and C $(0.1, 0.3)$ [m], respectively. In the condition in which the participants were required to use their right hand, the participants were asked to move their right hand from points A to C via point B. Conversely, when using their left hand, the participants were asked to move their left hand from points C to A via point B. The participants were asked to accomplish the movement within 1 s for each trial. The indicator circle corresponding to the position of the participants' hand and points A, B and C were displayed on a liquid crystal display placed in front of the participant.

To investigate the effect of the visual feedback control during the motor execution, two conditions were set. In the visible condition, the participants could always confirm the position of their hand with the indicator circle. In the invisible condition, the indicator circle disappeared as soon as a participant began a movement. After the movement, the indicator circle appeared, and the path of the movement was shown on the display to provide the knowledge of the results.

Four conditions, involving combinations of the hand factor (right and left) and vision factor (visible and invisible) were designed. Sixty trials were performed for each condition, and measured data from the last 50 trials were used in the analysis. Each trial was performed in the order of right-visible, right-invisible, left-visible, and left-invisible conditions.

The position of the participant's hand over a movement was measured at a sampling frequency of 1000 Hz.

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3.2 Analysis

A low-pass digital filter with a cutoff frequency of 8 Hz was applied to the measured data before the analysis. To facilitate the comparison of the right and left hand movements, the data for the left hand movements were inverted on the x-axis before the analysis. The data corresponding to a velocity of more than 0.04 m/s were used for the analysis.

Assuming that the movements in this experiment were produced by the shoulder and elbow joints driving in the horizontal plane, and considering an upper limb to be a two-link manipulator, the shoulder and elbow joint angles were calculated from the measured data of the participant's hand position. The joint angular velocity and acceleration were calculated from the time-series of the joint angle by using a differential method. Furthermore, the muscle torque MUS, net torque NET, and interaction torque INT of the shoulder and elbow joints were calculated using Equation (2). The physical parameters of the upper limb were derived from the literature (Nakano et al., 1999).

To evaluate the characteristics of each movement under each condition, certain parameters related to the movement were considered: Dir_b and Dir_e: direction of the movement path at the beginning and end, respectively; IOCIM, sum of the IOCIM of the shoulder and elbow joints; MUS, sum of the muscle torques of the shoulder and elbow joints; V_{max}, maximum velocity of the movement; Vr, ratio of V_y to V_{max}, where V_y denotes the velocity at the maximum point of the movement path on the y-axis; C_v, curvature during the maximum velocity; Err_{via} and Err_{end}: distance between the movement and via-point and between the movement and end point, respectively. Figure 2 illustrates the definitions of Dir_b, Dir_e, Err_{via} and Err_{end}.

A two-factor analysis of variance, pertaining to the hand (right and left) × vision (visible and invisible), was conducted. In addition, multiple comparisons were performed through Tukey's honestly significant difference test. The correlation coefficients between IOCIM and the other parameters were analyzed to investigate the effect of the IOCIM in the movements.

The data of trials with a movement duration ranging from 850 to 950 ms were used for the analysis. In the analysis of the right-visible, right-invisible, left-visible, and left-invisible conditions, 126, 55, 107, and 78 trials were considered, respectively.

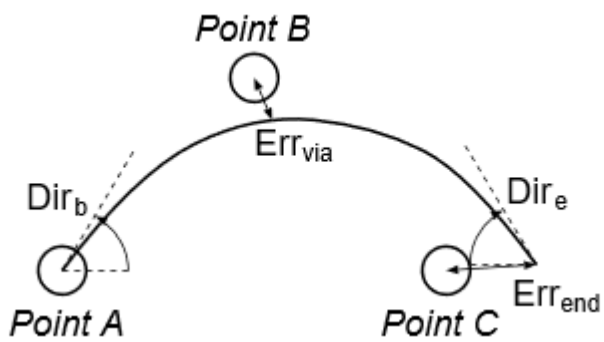

Figure 2 Definitions of Dir_b, Dir_e, Err_{via}, and Err_{end} to evaluate the path shape of the movement trajectory.

3.3 Results

Figure 3 depicts the path and velocity of the mean trajectory for each condition. Table 1 presents the results of the analysis of variance for each value described in section **3.2**.

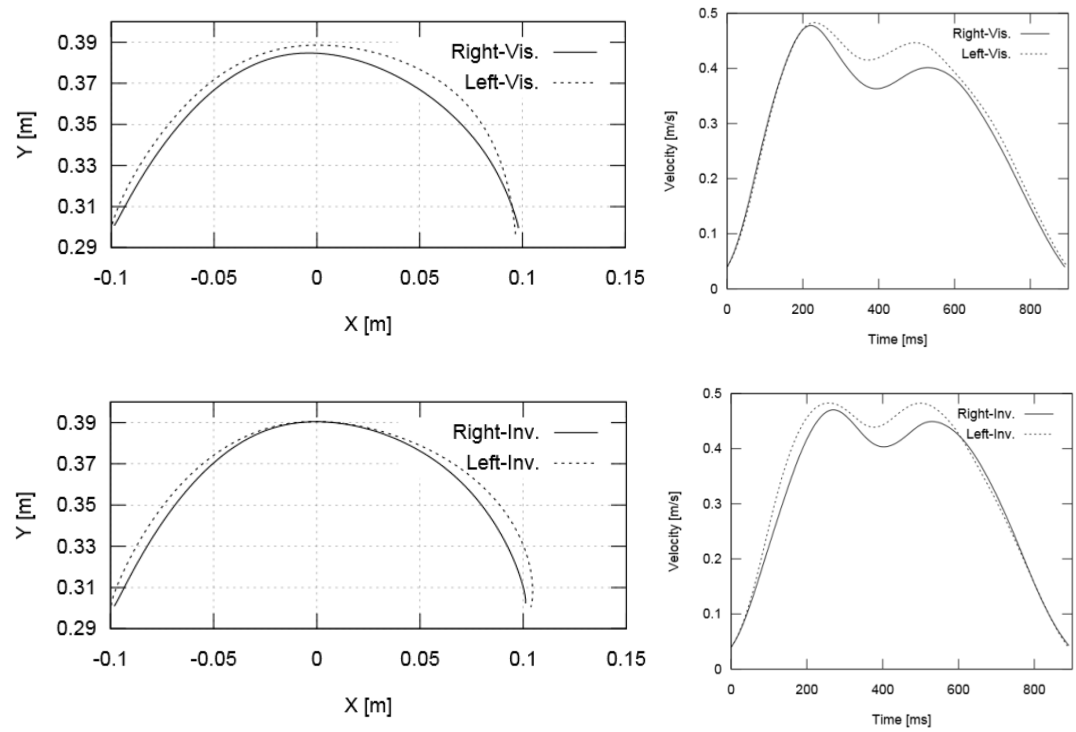

Figure 3 Path and velocity of the mean trajectories in four conditions (Right and Left hands × visible and invisible).

Table 1 Two-way analysis of variance (Hand × Vision) results for each parameter. Numbers and symbols (+:$p < .1$, *: $p < .05$, **: $p < .01$, and ***: $p < .001$) in the table indicate the p-values for the main effect of the factors (Hand and Vision) and the interaction (Hand × Vision).

	Main effect		Interaction		Main effect		Interaction
	Hand	Vision	Hand × Vision		Hand	Vision	Hand × Vision
Dir_b	***	*	+	V_r	**	.134	*
Dir_e	***	**	.524	C_v	*	***	**
IOCIM	***	.176	*	Err_{via}	.924	.259	***
MUS	***	***	.982	Err_{end}	***	***	.914
V_{max}	***	*	+				

Dir_b and Dir_e for the right hand were significantly greater than those for the left hand in both the vision conditions ($p < .001$), and C_v for the right hand was significantly greater than that for the left hand in the invisible condition ($p < .01$). These results indicate a difference in the shape of the paths corresponding to the right and left hands. The paths for the right and left hands were speculated to be inverted V-shapes and inverted U-shaped, respectively.

V_{max} for the left hand was significantly greater than that for the right hand in both the vision conditions (both $p < .001$). A significant difference was observed between the visible and invisible conditions in the case of the left hand ($p < .05$), although the

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corresponding difference for the right hand was not significant ($p > .999$). The effect of the vision availability in the task was more notable in the case of the left hand than in the case of the right hand.

V_r for the left hand was significantly greater than that for the right hand in the visible condition ($p < .01$), although a significant difference was not noted between the right and the left hand cases in the invisible condition ($p = .993$). The waveform of the movement velocity induced in the task exhibited two humps, as shown in Figure 3. The larger V_r for the left hand compared to that for the right hand highlights the difference between the hump peaks, and the valley for the left hand was noted to be more gradual than that for the right hand.

Err_{via} for the right hand was significantly larger than that for the left hand in the visible condition ($p < .05$), whereas it was significantly greater for the left hand compared to that for the right hand in the invisible condition ($p < .01$). A significant difference in Err_{end} for the right and the left hands was not observed in any of the vision conditions (visible: $p = .136$, and invisible: $p = .299$).

The MUS for the left hand was significantly greater than that for the right hand in both the vision conditions (both $p < .001$). In terms of the vision conditions, the MUS in the invisible condition was significantly greater than that in the visible condition for both the hands ($p < .001$).

The IOCIM for the right hand was significantly greater than for the left hand in the visible condition ($p < .05$), whereas a significant difference between the two hands was not observed in the invisible condition ($p = .877$). In terms of the vision condition, the IOCIM in the invisible condition was significantly greater than that in the visible condition for the left hand ($p < .05$), whereas a significant difference was not observed between the vision conditions for the right hand ($p = .848$).

The correlation coefficient r between the IOCIM and other parameters was calculated to investigate the effect of the IOCIM. The values of the correlation coefficient were as follows: Dir_b: $r = -0.242, p < .001$; Dir_e: $r = -0.339, p < .001$; C_v: $r = -0.307, p < .001$; V_{max}: $r = -0.159,\ p < .01$; V_r: $r = -0.559, p < .001$; Err_{via}: $r = -0.044, p = .404$; Err_{end}: $r = 0.054, p = .303$ and MUS: $r = 0.038, p = .464$. The IOCIM was correlated with the shape of the movement path and movement velocity and not correlated with the error of the movement regarded as the movement accuracy.

4.0 SIMULATION EXPERIMENT

In the existing studies, the relation between the IOCIM and movement characteristics was examined; however, the influence of the IOCIM on the generated movement was not considered. In the simulation experiment described herein, the hand trajectories were computed under various IOCIM values.

To define trajectories with various IOCIM values, first, the time-series of the joint torques of the minimum commanded torque change trajectory (MTC) (Nakano et al., 1999) satisfying the constraint condition was computed. Second, the time-series of the joint torques $\tau_{s,e}(0)$, $\tau_{s,e}(\Delta t)$, $\tau_{s,e}(2\Delta t), \cdots$, $\tau_{s,e}(t_f)$ were modulated to increase or decrease the IOCIM of the trajectory. Here, τ_s and τ_e denote the shoulder and elbow joint torques of the MTC, respectively; Δt denotes the time step for discretization; and

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t_f denotes the movement duration. Next, an evaluation function F_e was defined as in Equation (4).

$$F_e = F_c + \lambda \cdot \mathrm{IOCIM} \quad (4)$$

where F_c denotes the constraint condition defined in terms of the squared difference between the specified position(s) (e.g., an end point and a via-point) of a trajectory and the position(s) corresponding to the specified position(s) of the computed trajectory, the IOCIM is as defined in Equation (3), and λ is a non-negative value that decreases with each iteration of the computation, based on simulated annealing.

Finally, a gradient of F_e with respect to $\tau_{s,e}$ at each time was calculated, and $\tau_{s,e}$ was modulated by using this gradient. The IOCIM of the trajectory modulated $\tau_{s,e}$ was greater or less than that of the MTC. Figure 4 shows the flowchart to compute a trajectory with different IOCIM from a minimum commanded torque change trajectory , which is explained as above.

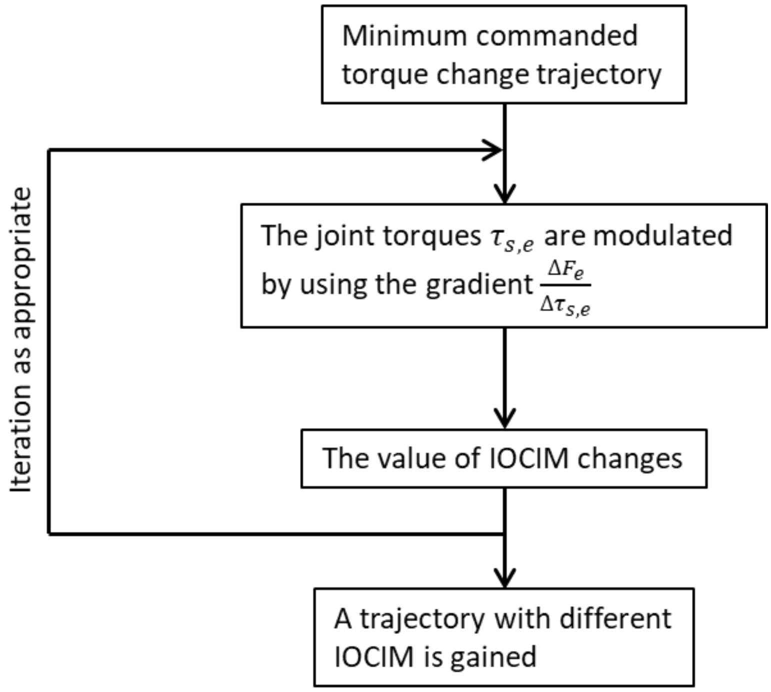

Figure 4 The flowchart to compute a trajectory with different IOCIM from a minimum commanded torque change trajectory.

A point-to-point movement and via-point movement were examined. Both movements were assumed to be produced in the horizontal plane. The simulated trajectories of the former and latter movements were compared with the previously reported results and the results of the measurement experiment performed in this study, respectively.

4.1 Point-to-point movement

The position of the shoulder joint was set as the origin of the coordinates. The start and end points were set as $(-0.1, 0.2)$ [m] and $(-0.3, 0.4)$ [m], respectively, and the

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movement duration was set as 500 ms. Trajectories with an IOCIM larger and smaller than that of the MTC, labeled Large and Small, respectively, were computed. Figure 5 shows the path and velocity of the MTC (solid line), Large (dashed line), and Small (dotted line). The IOCIM values for the MTC, Large, and Small were 0.376, 0.697, and 0.039, respectively.

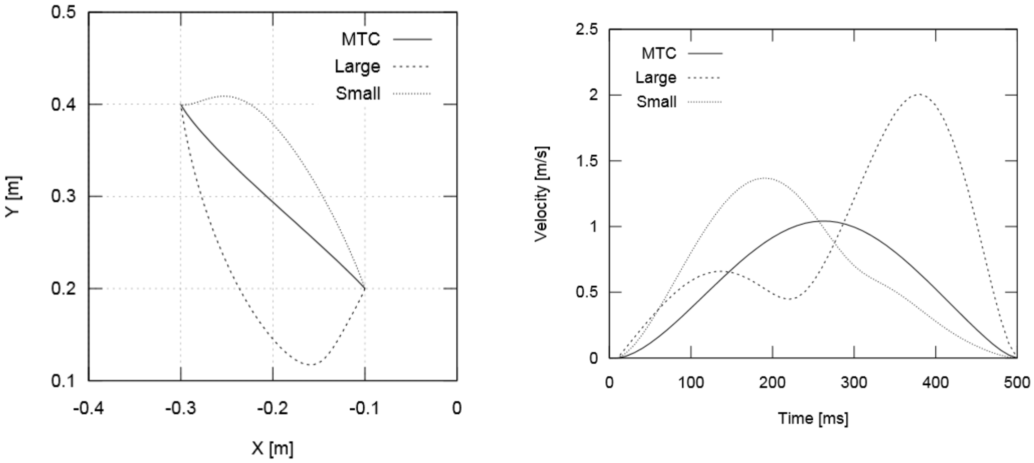

Figure 5 Path and velocity of the simulated trajectories for a point-to-point movement.

The path of the MTC was almost a straight line connecting the start and end points, which is a characteristic of an ordinal human movement. In contrast, the paths of Large and Small were curved inward and outward, respectively. In a natural and ordinary condition, humans rarely produce such curved trajectories, although the movement trajectory can be curved in certain conditions, as reported in certain studies. Specifically, when the movement duration is extremely small (Suzuki & Uno, 2000), the path of the trajectory may be curved inward, similar to Large. The result demonstrates the significance of the IOCIM. Moreover, when a participant performs a point-to-point movement with a non-dominant hand (Sainburg & Kalakanis, 2000; Bagesteiro & Sainburg, 2002), the path of a trajectory is curved outward, similar to Small. The velocity profiles of Large and Small were similar to those reported previously. In other words, the experiments in this study could reproduce the results of the previous studies by simply modulating the IOCIM.

4.2 Via-point movement

The position of the shoulder joint was set as the origin of the coordinates. The start and end points were set as $(-0.3, 0.3)$ [m] and $(-0.1, 0.3)$ [m], respectively, and the via-point was set as $(-0.2, 0.39)$. The time of passing the via-point was set as 450 ms, and the movement duration was set as 900 ms. The setup was nearly identical to that of the measurement experiment performed in this work. The MTC was considered as the ordinal movement, and certain trajectories with different IOCIM values were computed. Figure 6 depicts the path and velocity of these trajectories.

It can be noted that the path shape and velocity profile do not consistently change with the various IOCIM values, as in the case of the point-to-point movement. The r values between the IOCIM and parameters representing the trajectory characteristics were as

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follows: Dir_b: $r = 0.013, p = 0.961$; Dir_e: $r = -0.857, p < .001$; C_v: $r = 0.762, p < .001$; V_{max}: $r = -0.992\ p < .001$; V_r: $r = 0.951, p < .001$ and MUS: $r = -0.990, p < .001$. Note that the movement errors were always zero for the computed trajectory, and thus, therefore Err_{via} and Err_{end} could not be defined in the current experiment. A significant correlation was noted between IOCIM and certain parameters, although the results did not correspond to the data obtained in the measurement experiment.

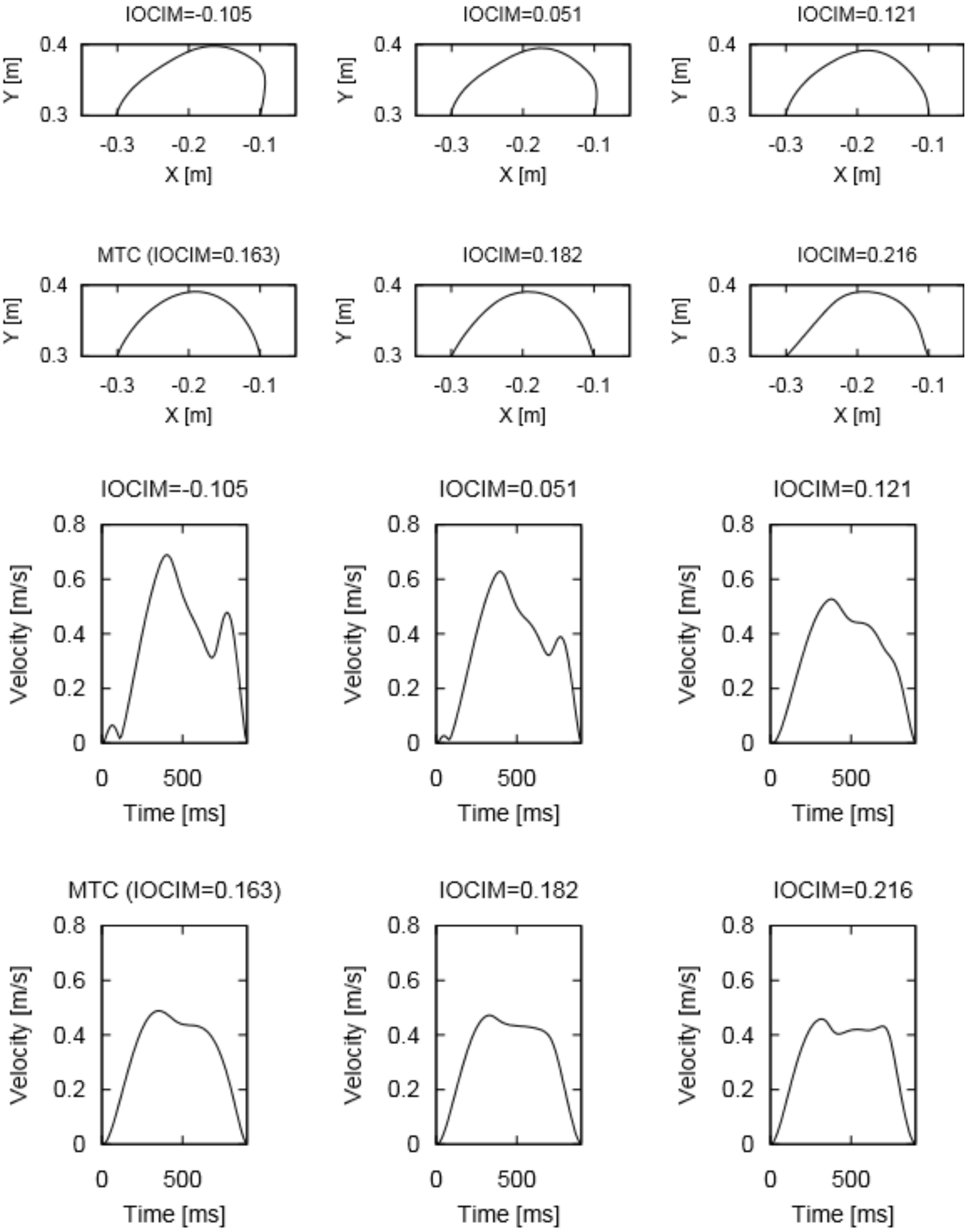

Figure 6 Path and velocity of the simulated trajectories with specific start, via-, and end points.

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5.0 DISCUSSION

The purpose of this study was to investigate the effect of the interaction torque on the motor control. Previous studies focusing on the interaction torque have discussed this aspect based on computer simulations (Hirashima et al., 2003), although relatively simple motor tasks were evaluated such as a single-joint movement (Gribble & Ostry, 1999), a point-to-point movement (Sainburg & Kalakanis, 2000; Bagesteiro & Sainburg, 2002) and a squatting movement (Fujisawa et al., 2016). In this study, the motor task was a via-point movement, which is considered to be more difficult than a point-to-point movement, and both measurement and simulation experiments were performed to compare the two movements.

In the measurement experiment, the influence of the hand dominance and vision during the execution of the movement on the IOCIM was analyzed. The trajectories produced by the dominant and non-dominant hands were different in terms of the path shape and velocity waveforms; there were significant differences between the dominant and non-dominant hands in Dir_b, Dir_e and V_{max} (all $p < .001$) for the visible and invisible conditions. The focus of this study was on examining whether these differences are related to the interaction torque.

The right hand IOCIM was significantly greater than that of the left hand in the visible condition ($p < .05$). In other words, the dominant hand more effectively exploits the effect of the IOCIM than the non-dominant hand. A similar result was reported in previous studies, in which a point-to-point movement was adopted as the motor task (Bagesteiro & Sainburg, 2002). Nevertheless, a significant difference in the IOCIM between the right and left hands was not observed in the invisible condition ($p = .877$). This finding indicates that the advantage of the dominant hand on IOCIM is not always apparent, and it is speculated that this advantage is a result of the online feedback using visual information during movement execution. It is speculated that it is hard to compute the motor commands taking into account the effect of the IOCIM in motor planning.

The IOCIM was significantly correlated with certain parameters that represented the trajectory characteristics. Note that there exist innumerable varied trajectories, which have nearly equivalent IOCIM values. The significant correlation between the IOCIM and the parameters suggests that the variation of IOCIM can produce consistent characteristics of a trajectory. However, in this study, the causal relationship between the IOCIM and the parameters was not investigated, and it is unclear whether the variation in the trajectory was attributable to the difference in the IOCIM.

The correlation between the IOCIM and trajectory errors, evaluated as Err_{via} ($r = -0.044, p = .404$) and Err_{end} ($r = 0.054, p = .303$), was not significant. Thus, a consistent trend for the increase in the movement accuracy with an effective IOCIM or the reduction in the torque efficiency with an increased movement accuracy was not observed. Previous studies that focused on the movement accuracy and evaluated this aspect as the distance between the path of the trajectory and imposed points reported that the movement error was smaller in the neighborhood of a imposed point (Todorov & Jordan, 2002) and at the point with a low velocity (Morishige et al., 2004). Hirashima et al. (2003) speculated that the interaction torque impeding the wrist joint torque during the pitching motion helped stabilize the movement. Moreover, it was noted that the motor control system of the non-dominant hand led to ineffective movements in terms

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of the joint torque, although this ineffectiveness could make the movement robust against unexpected perturbation during execution (Bagesteiro & Sainburg, 2003). Nevertheless, in the via-point movement adopted in this study, the IOCIM was not correlated with the movement error, and the interaction torque did not appear to influence the movement accuracy. The ratio of the net torque to the muscle torque (NET/MUS) per time-series of the joint torque was also analyzed, although this value was not low in the neighborhood of the via-point, and a significant correlation with Err_{via} was not observed.

In the simulation experiments, certain trajectories with interesting feature were evaluated by artificially modulating the IOCIM for a point-to-point movement. The characteristics of the trajectory with decreased IOCIM corresponded with those of an actual movement produced by the non-dominant hand. Moreover, the characteristics of the trajectory with increased IOCIM were similar to those of the computed trajectory, leading to a minimized movement duration. In particular, to minimize the movement duration, it is necessary to move the joints faster and use the joint torque effectively. Thus, the reproduction of the trajectory characteristics with the minimum movement duration by increasing the IOCIM seems reasonable.

For a via-point movement, the influence of the IOCIM was less apparent than that in the point-to-point movement, both in the measurement and simulation experiments. This phenomenon likely occurred because the task-constraint of a via-point movement is higher than that of a point-to-point movement, which limits the variation of the movement trajectory. In this study as well as the previous studies, the participants produced similar movements under the same experimental condition, even though they could produce varied movements (Flash & Hogan, 1985; Flanagan & Rao, 1995). It has been conjectured that humans plan a movement based on the optimization of certain criteria related to a movement, for example, smoothness (Flash & Hogan, 1985; Nakano et al., 1999), accuracy (Harris & Wolpert, 1998), simplicity (Sakaguchi & Ikeda, 2007; Karniel, 2013; Oyama & Ito, 2020) and neural effort (Dounskaia & Shimansky, 2016). Consequently, the produced movement is nearly always the same and determinate based on the optimization solution of the selected criterion. Even when the motor control system considers the IOCIM as the criterion for the motor planning, the evaluation of the IOCIM is undervalued if other criteria that are more critical to compute the motor commands and realize the task degrade. Because the task-constraint of a point-to-point movement was smaller than that for a via-point movement, the motor control system could vary the movement taking into account the IOCIM. Specifically, the via-point movement was excessively restrictive as a motor task to observe the diverse movements affected by the IOCIM. Raj et al. (2020) reported that individuals with stroke use the effect of interaction torque less than healthy individuals. It is speculated that taming adeptly interaction torque is hard and expensive for the motor control system, therefore the difference in IOCIM did not clearly appear in the via-point movement analyzed in this study.

6.0 CONCLUSION

In this study, the efficiency of the interaction torque in human upper limb movements was investigated. A via-point movement, which is considered to be a more difficult motor task than a point-to-point movement, which has been usually adopted in previous studies, was examined. The efficiency of the interaction torque was higher for the dominant hand than for the non-dominant hand in a via-point movement when visual information was available (ANOVA, $p < .05$). Moreover, the interaction torque did not contribute to the movement accuracy, in contrast to the previously reported results (there were no correlation between the interaction torque and movement errors). It is conjectured that the efficiency of the interaction torque can be considered as one of the criteria for motor planning, as it influences the characteristics of a certain movement, although it is hard to consider the influence of the interaction torque over other criteria relevant for the task-constraint. It is considered that the motor control system controls the effect of the interaction torque with the online feedback when the difficulty of a motor task is extremely high.

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